Can Primordial Black Holes be the Dark Matter?

S. Clesse
RWTH Aachen University

IRN Terascale conference, Montpellier
3rd July 2017

Outline

Outline

- LIGO and the strange black hole mergers

Outline

- LIGO and the strange black hole mergers
- A good Dark Matter candidate

Outline

- LIGO and the strange black hole mergers
- A good Dark Matter candidate
- A formation model from Hybrid Inflation

Outline

- LIGO and the strange black hole mergers
- A good Dark Matter candidate
- A formation model from Hybrid Inflation
- Constraints on PBH abundances

Outline

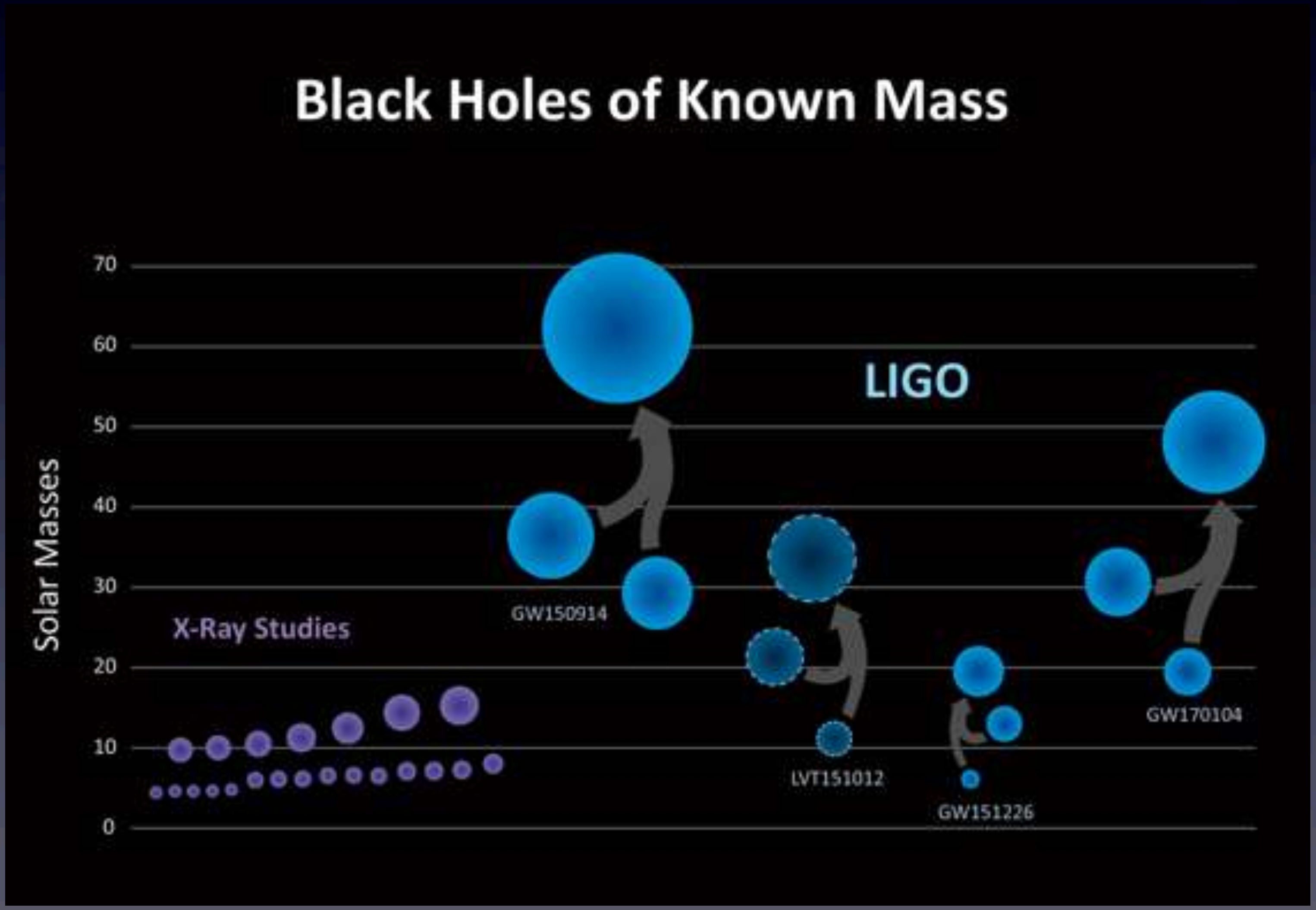
- LIGO and the strange black hole mergers
- A good Dark Matter candidate
- A formation model from Hybrid Inflation
- Constraints on PBH abundances
- Five Hints for PBH Dark Matter

Outline

- LIGO and the strange black hole mergers
- A good Dark Matter candidate
- A formation model from Hybrid Inflation
- Constraints on PBH abundances
- Five Hints for PBH Dark Matter
- Pros vs. cons, and future prospects

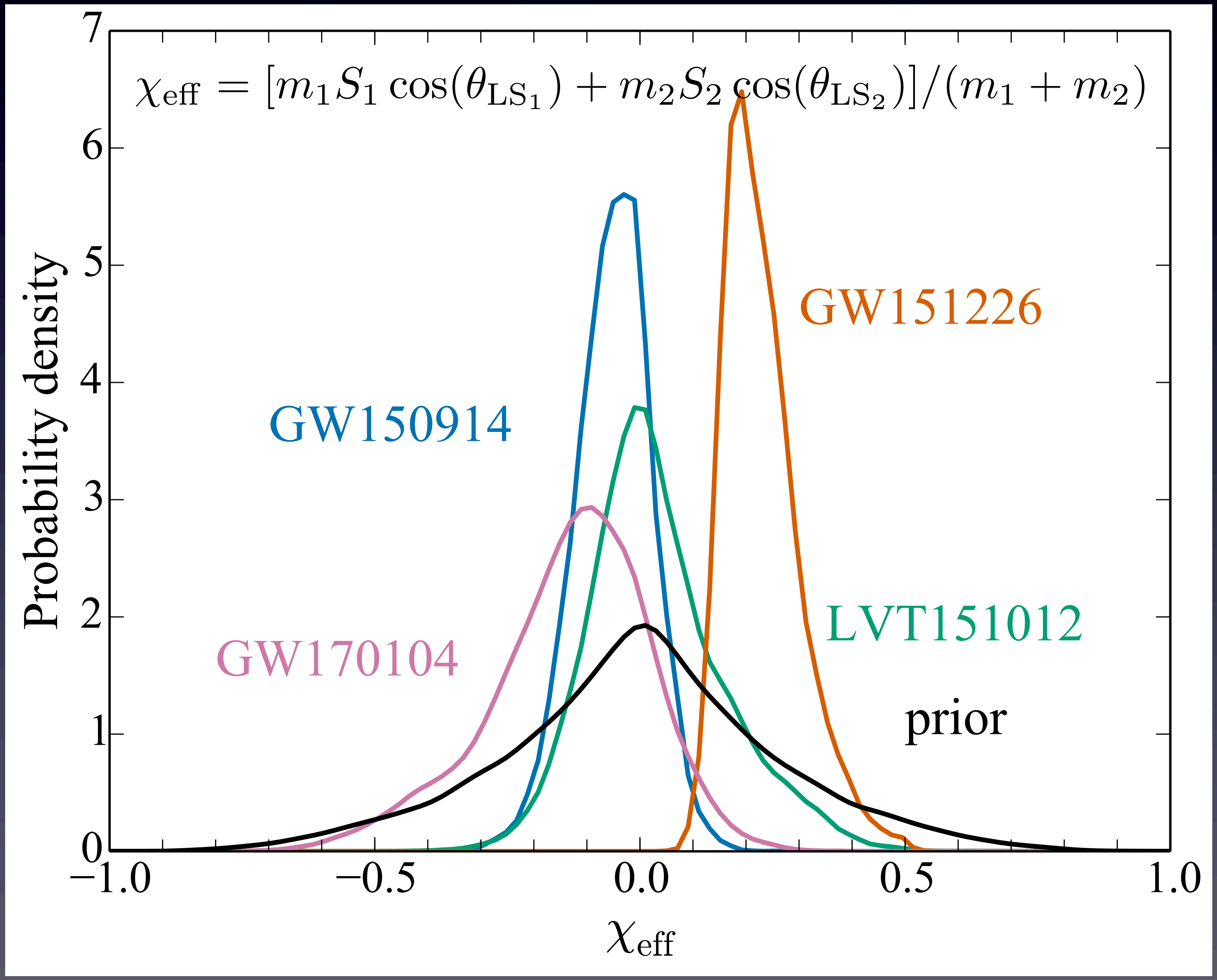
LIGO and the strange BH mergers

- Unexpected large masses for GW150914
- 3 other events > 15 Msun (6 events not yet released)
- Inferred rates: 14-158 $Gpc^{-3}\ yr^{-1}$
- Non-aligned, low spins



LIGO and the strange BH mergers

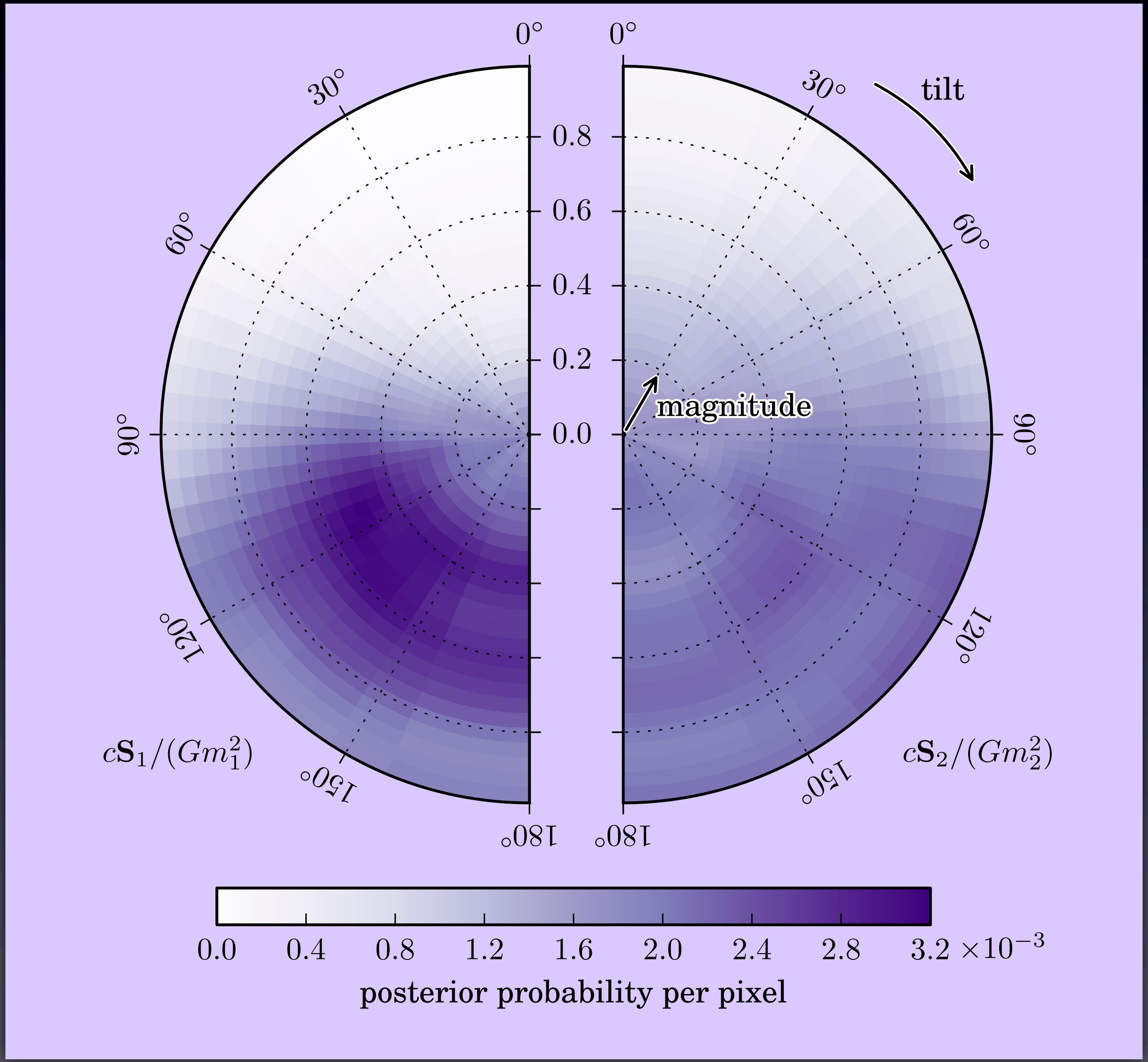
- Unexpected large masses for GW150914
- 3 other events > 15 Msun (6 events not yet released)
- Inferred rates: 14-158 Gpc^{-3} yr^{-1}
- Non-aligned, low spins



Adv.LIGO/VIRGO June release (supl. material)

LIGO and the strange BH mergers

- Unexpected large masses for GW150914
- 3 other events > 15 Msun (6 events not yet released)
- Inferred rates: 14-158 Gpc^{-3} yr^{-1}
- Non-aligned, low spins



Adv.LIGO/VIRGO June release (supl. material)

Confirmation of « a new population of black holes »

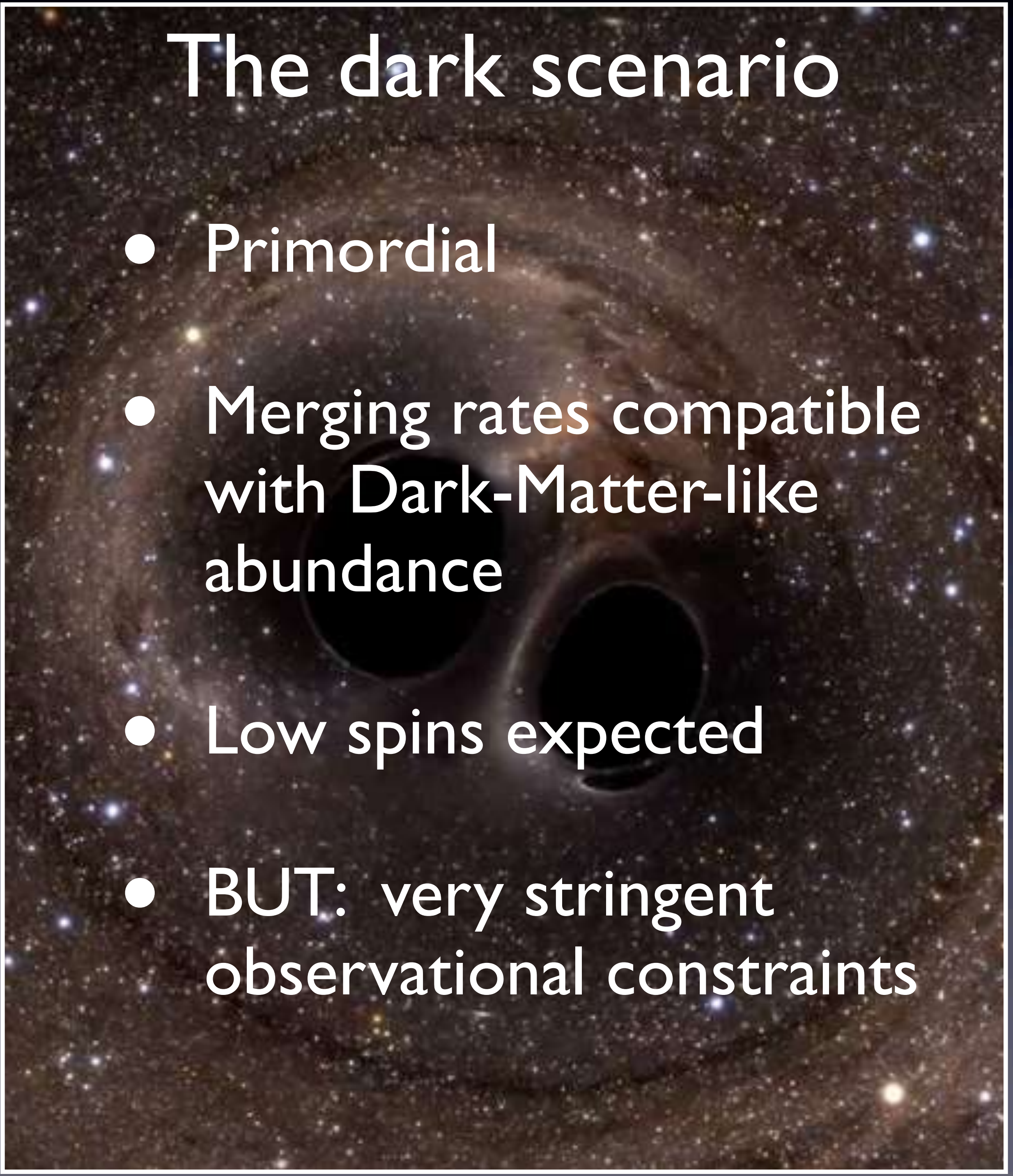
LIGO and the strange BH mergers

LIGO and the strange BH mergers

LIGO and the strange BH mergers

The bright scenario

- From star explosion
- Low-metallicity environment
- Super-dense clusters
- BUT: why so massive?
- BUT: unrealistic rates
- Need a new model...



The dark scenario

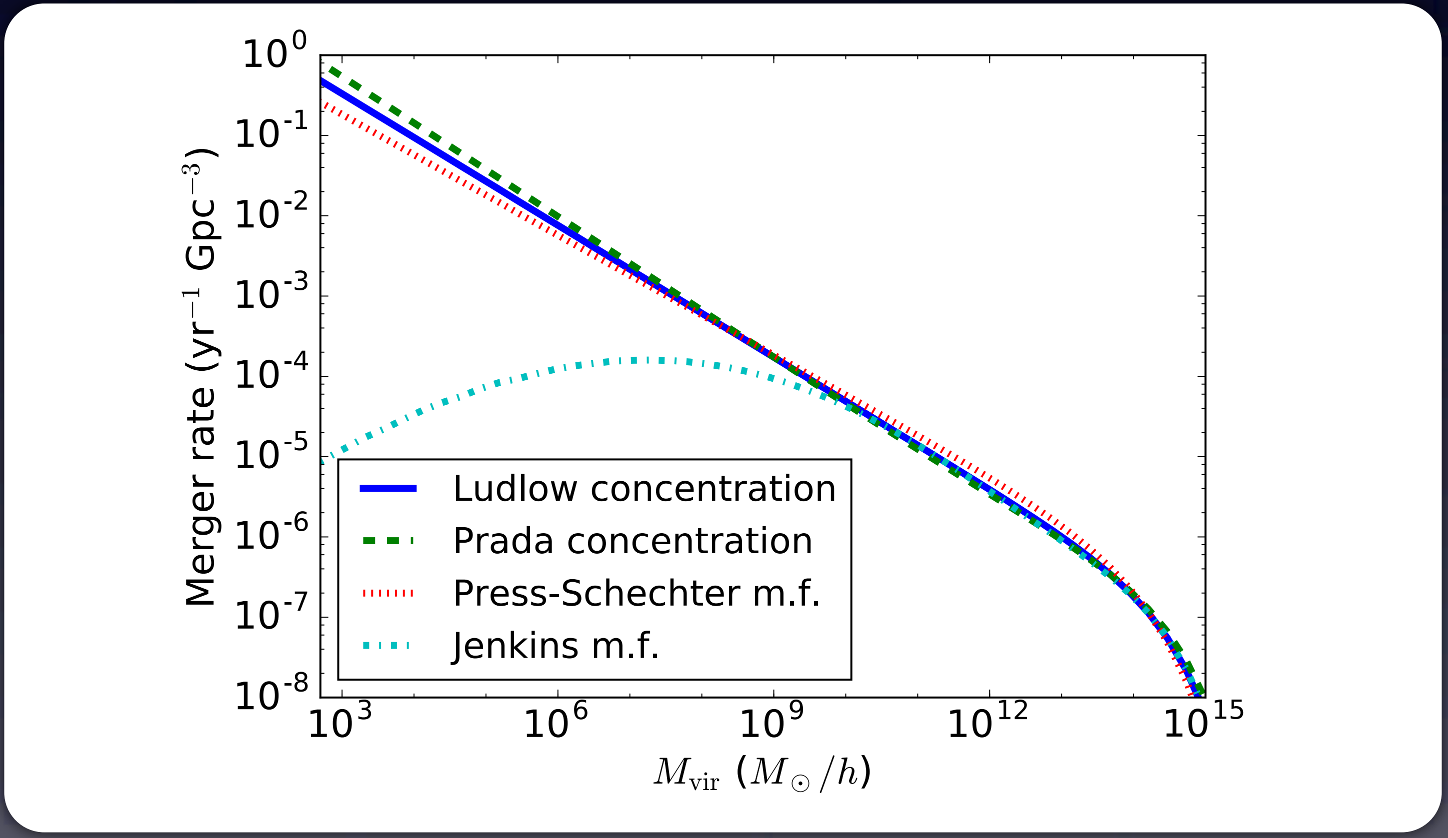
- Primordial
- Merging rates compatible with Dark-Matter-like abundance
- Low spins expected
- BUT: very stringent observational constraints

In March 2016...

- S. Bird et al., 1603.00464
  Monochromatic spectrum, extended halo mass function

$$\tau_{\rm merg} \sim 2 f_{\rm HMF} f_{\rm DM} \left(M_{\rm crit.halo}/400 M_\odot\right)^{-11/21} {\rm Gpc}^{-3}{\rm yr}^{-1}$$

Most mergings come from mini-halos



In March 2016...

- S. Bird et al., 1603.00464
  Monochromatic spectrum, extended halo mass function

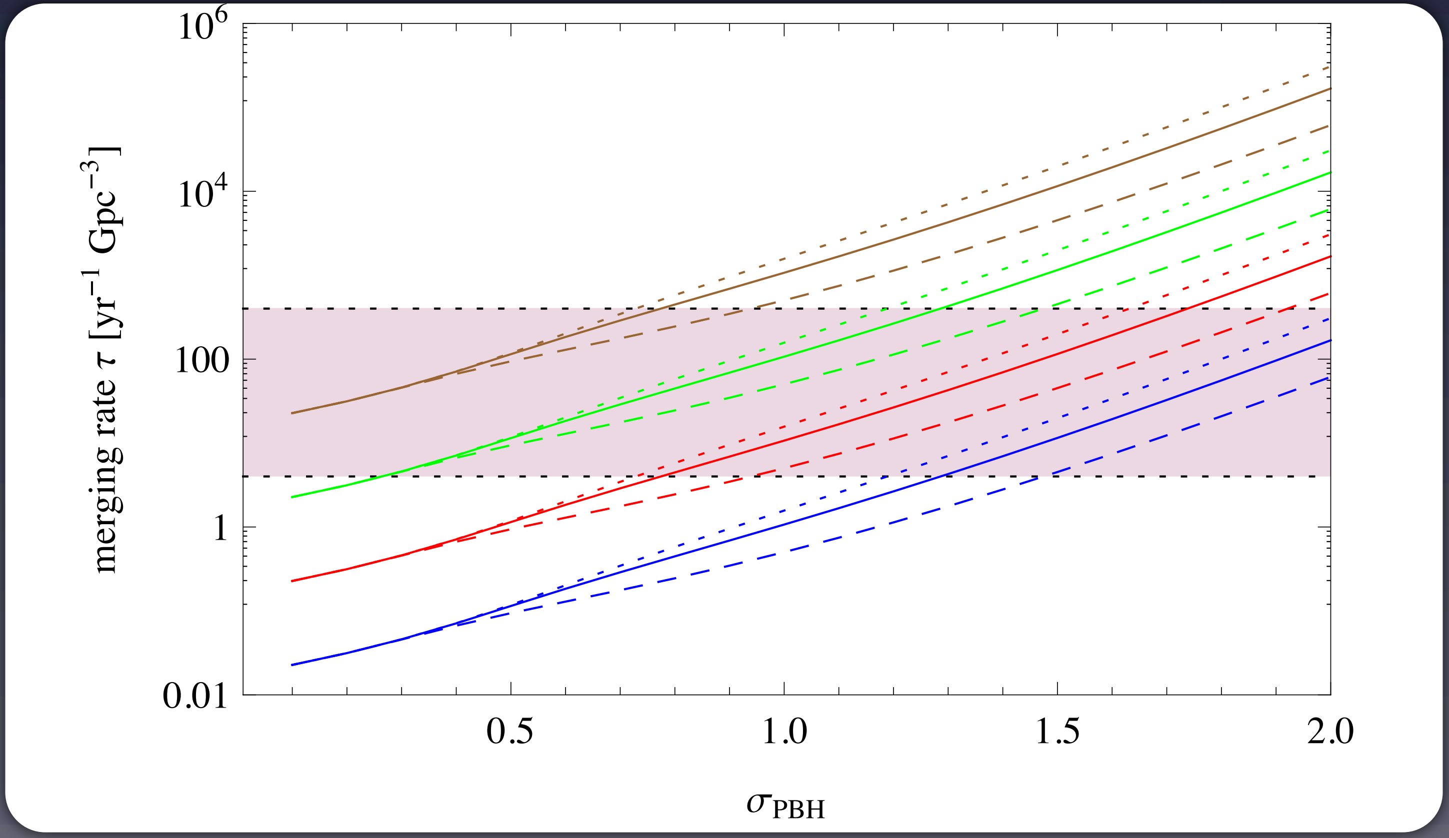
$$\tau_{\rm merg} \sim 2 f_{\rm HMF} f_{\rm DM} \left(M_{\rm crit.halo}/400 M_\odot\right)^{-11/21} {\rm Gpc}^{-3}{\rm yr}^{-1}$$

Most mergings come from mini-halos

- S.C., J. Garcìa-Bellido, 1603.05234
  Broad mass spectrum, natural clustering scale

$$\tau_{\rm merg} \sim f_{\rm DM} 10^{-8} \delta^{\rm loc.}_{\rm PBH} {\rm Gpc}^{-3}{\rm yr}^{-1}$$

Faint Dwarf Galaxies or Globular Clusters



In March 2016...

- S. Bird et al., 1603.00464
  Monochromatic spectrum, extended halo mass function

$$\tau_{\rm merg} \sim 2 f_{\rm HMF} f_{\rm DM} \left(M_{\rm crit.halo}/400 M_\odot\right)^{-11/21} {\rm Gpc}^{-3}{\rm yr}^{-1}$$

Most mergings come from mini-halos

- S.C., J. Garcìa-Bellido, 1603.05234
  Broad mass spectrum, natural clustering scale

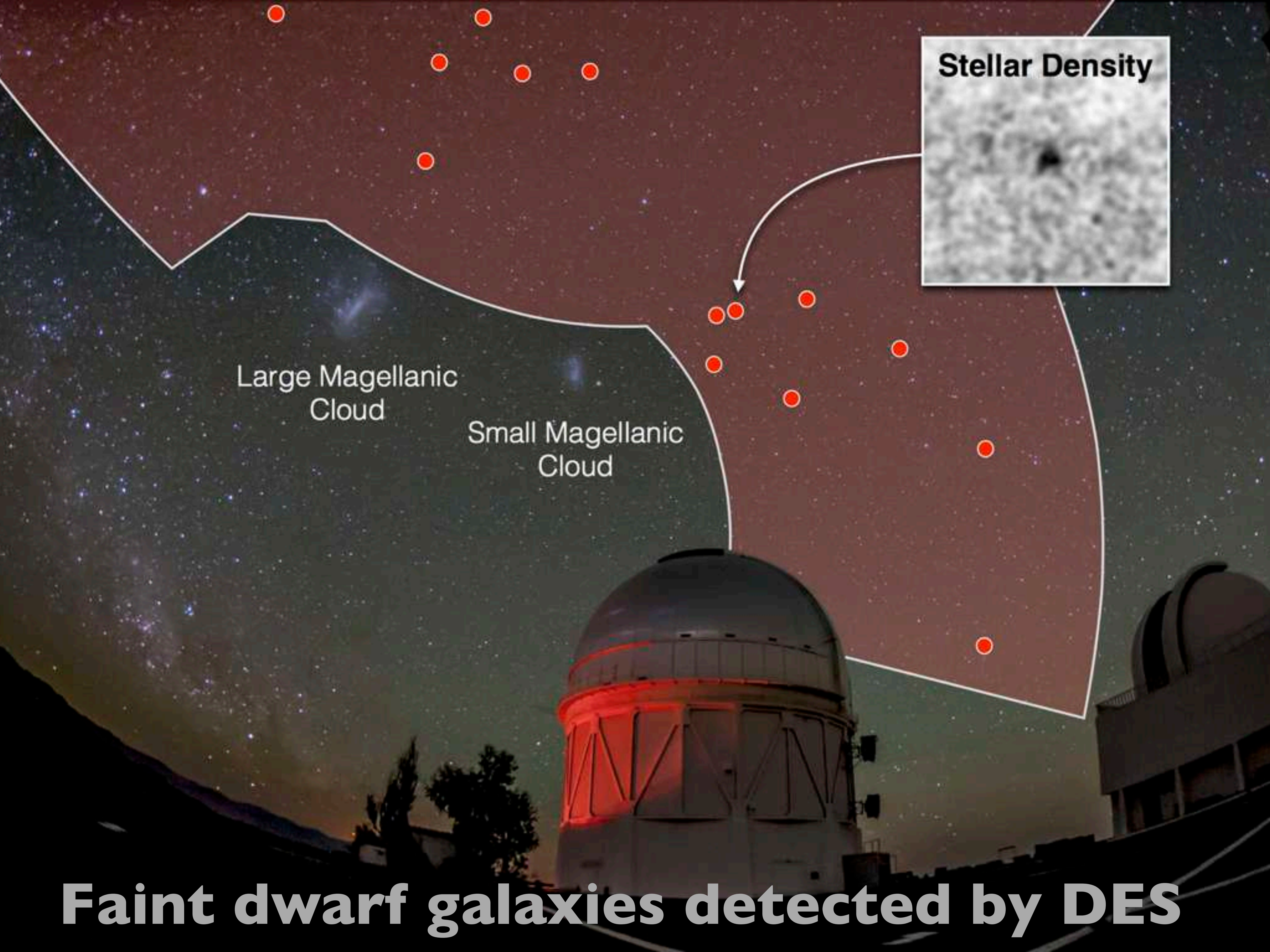
$$\tau_{\rm merg} \sim f_{\rm DM} 10^{-8} \delta_{\rm PBH}^{\rm loc.} {\rm Gpc}^{-3}{\rm yr}^{-1}$$

Faint Dwarf Galaxies or Globular Clusters

- M. Sasaki et al., 1603.08338
  Monochromatic spectrum, BH binaries from Early Universe

$$\tau_{\rm merg} \sim f_{\rm DM} 10^{4} {\rm Gpc}^{-3}{\rm yr}^{-1}$$

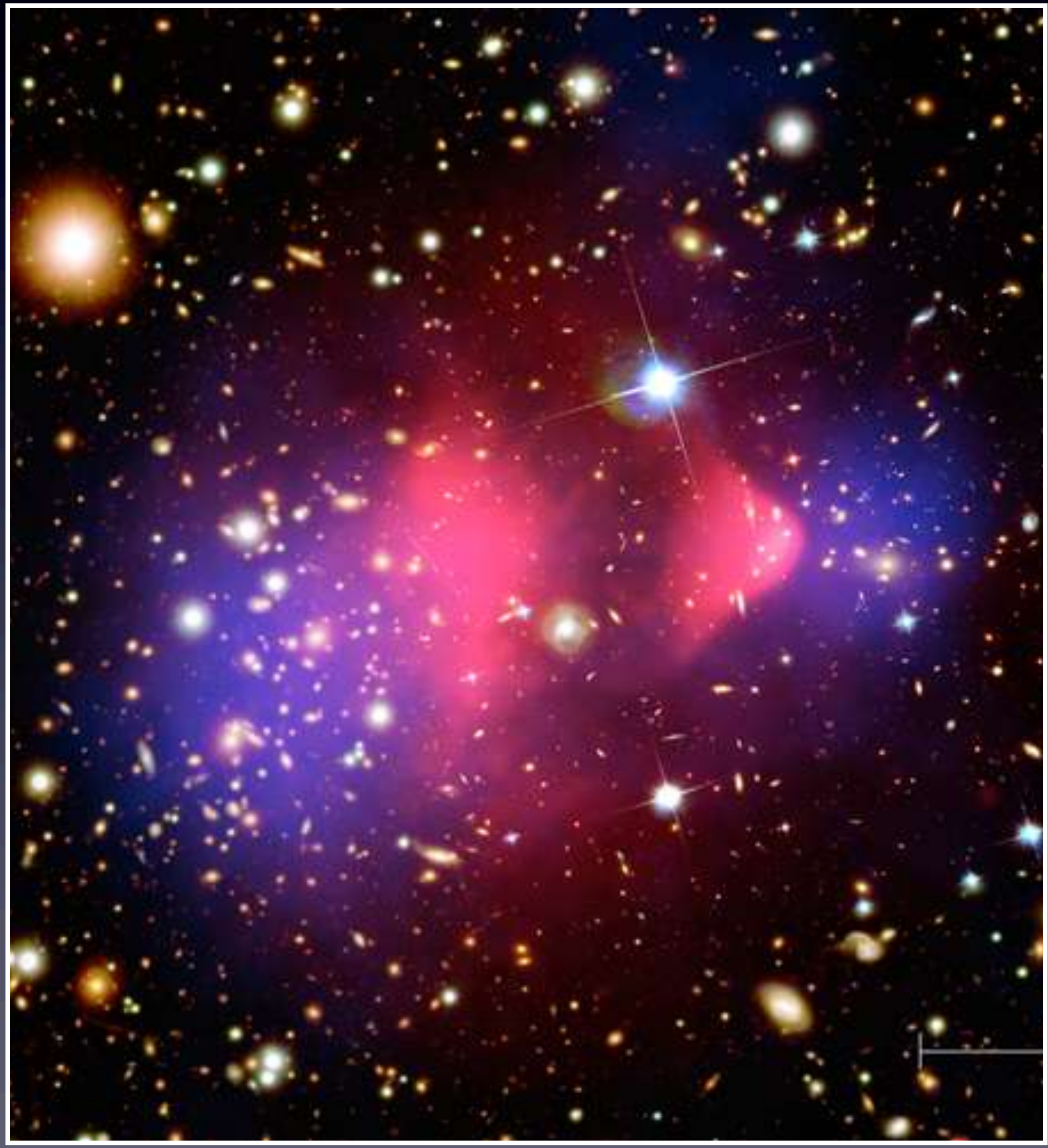
cannot be the Dark Matter except if PBHs are initially clustered

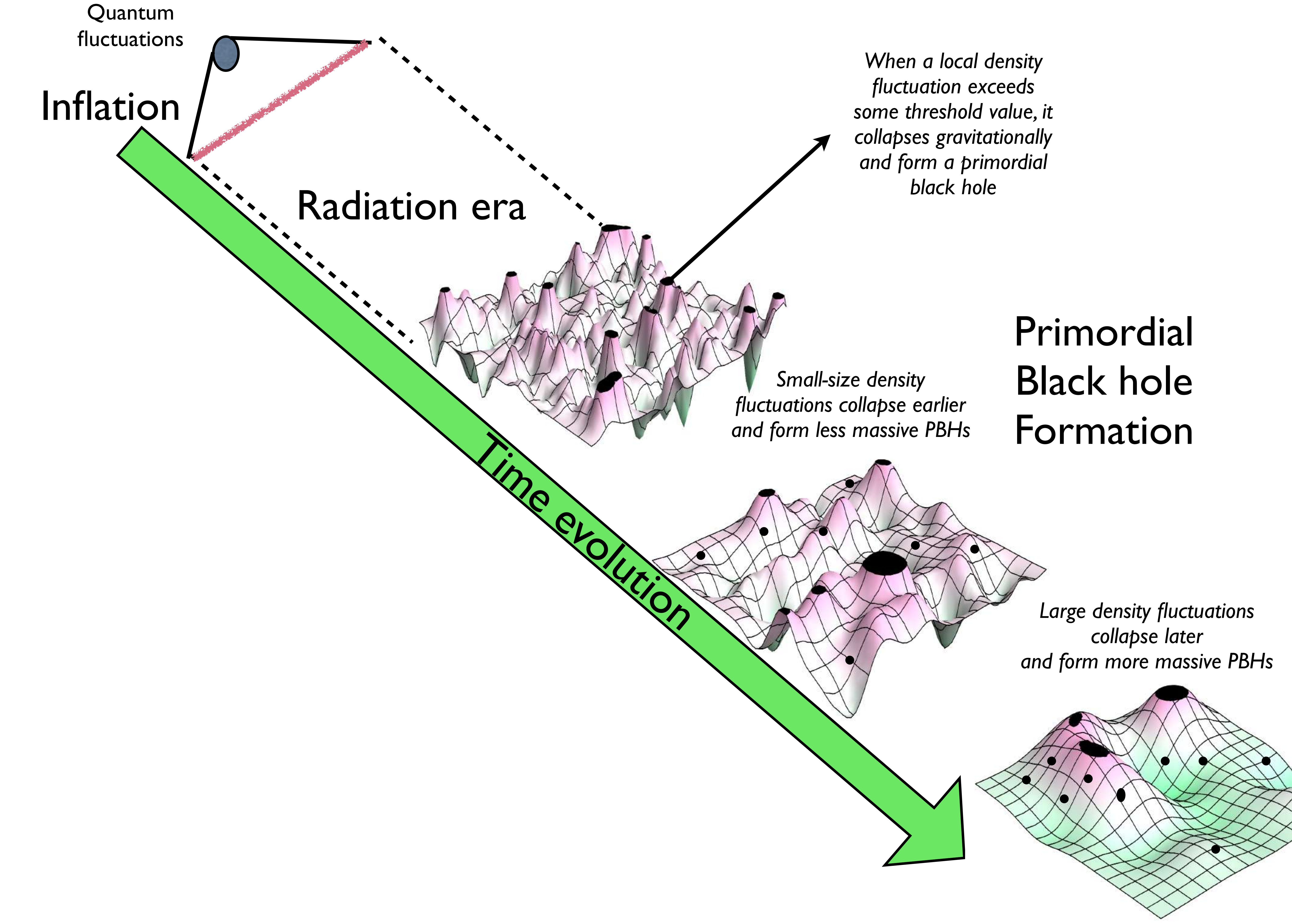


Faint dwarf galaxies detected by DES

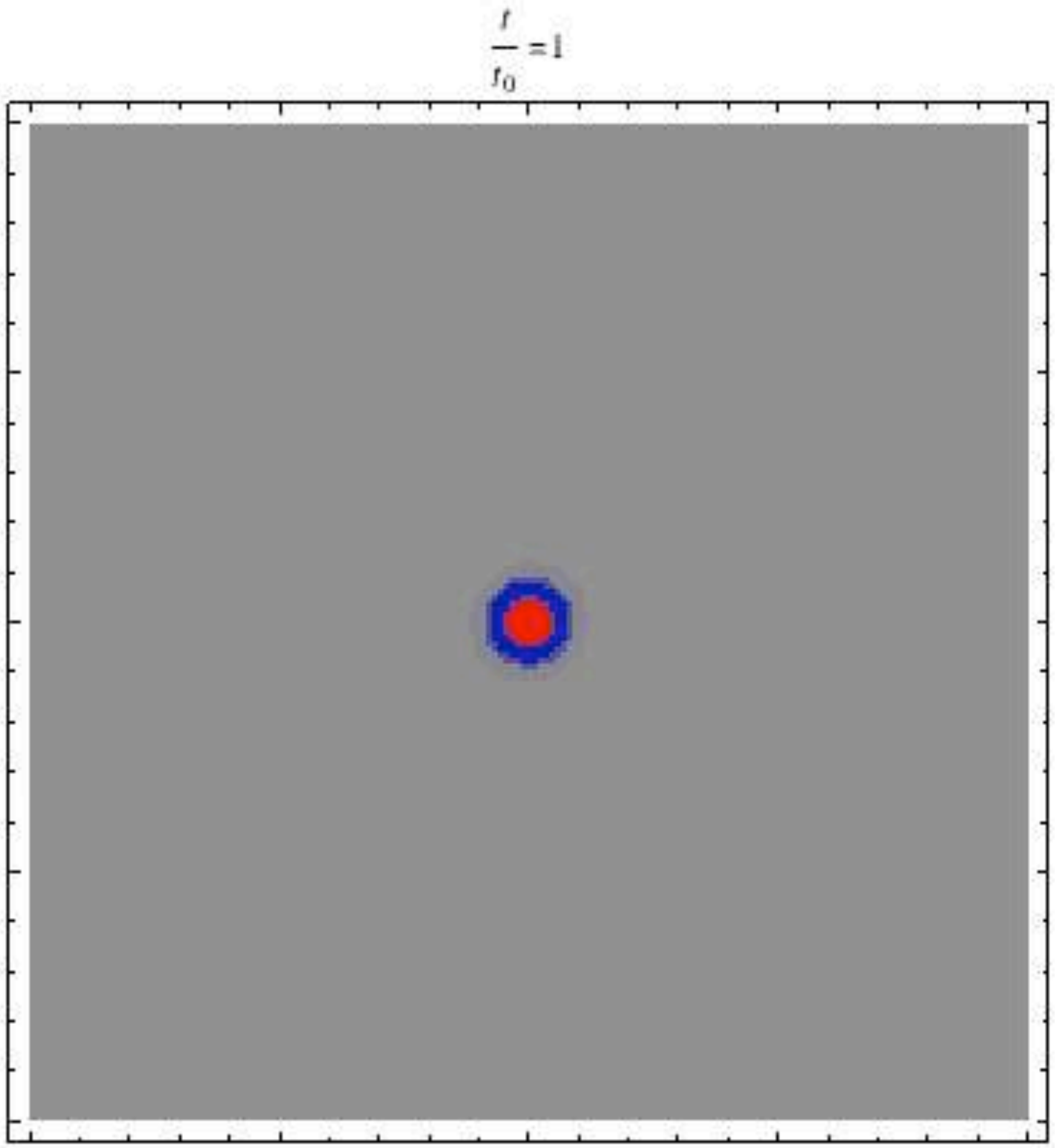
A good Dark Matter candidate

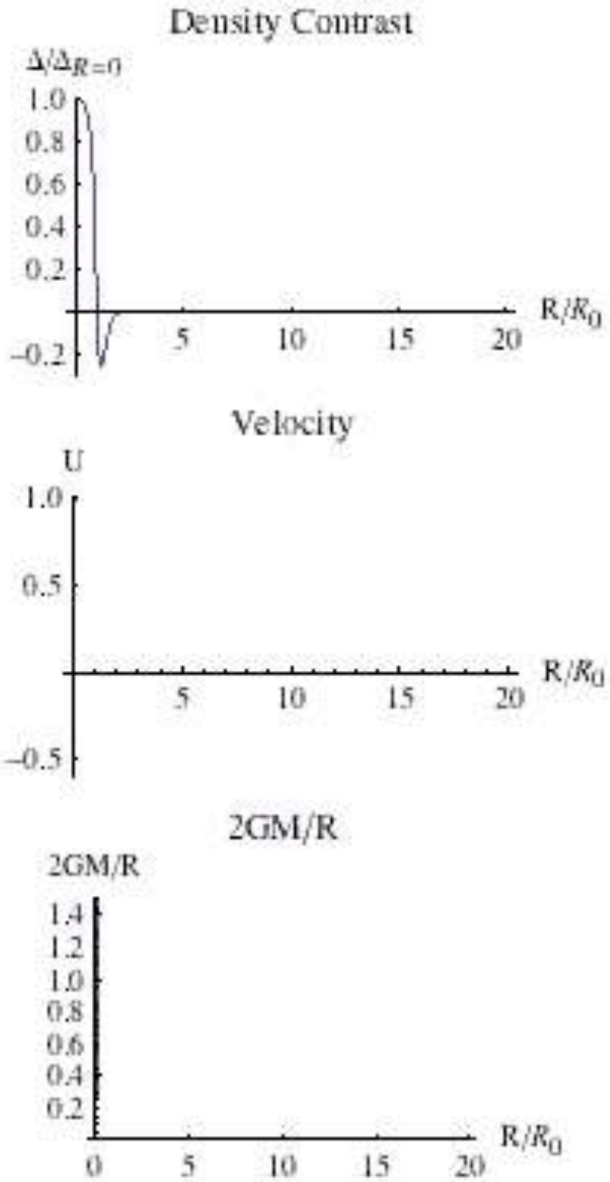
- Do not emit light by nature
- Non-relativistic
- Nearly collisionless
- Formed in the early Universe

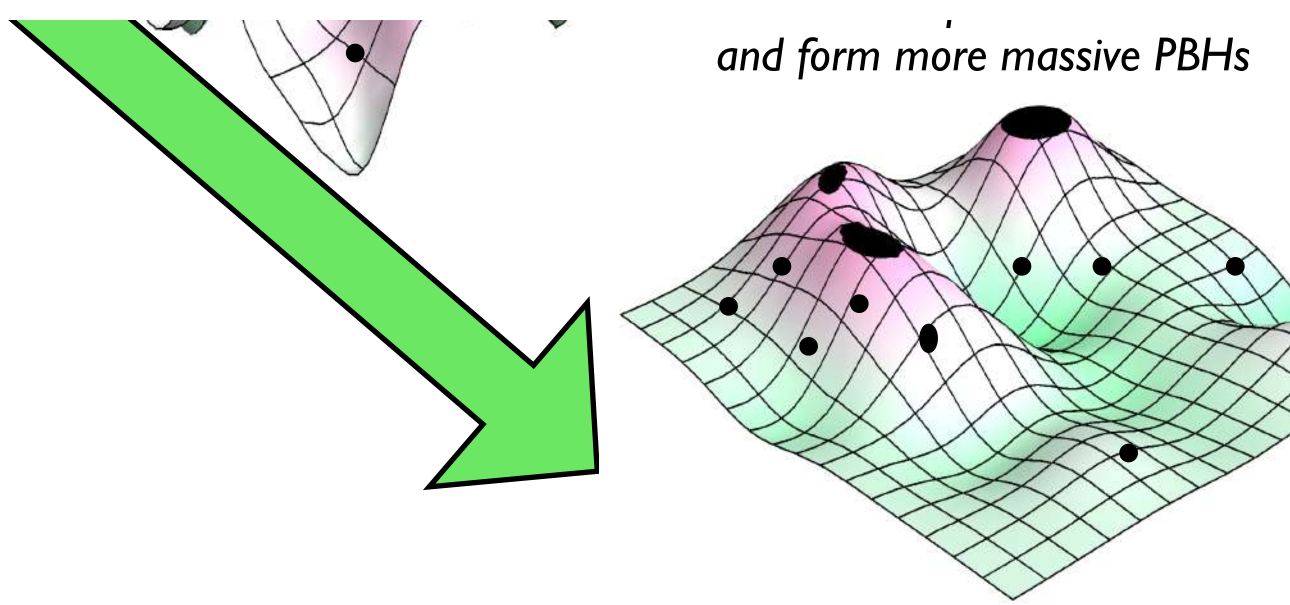


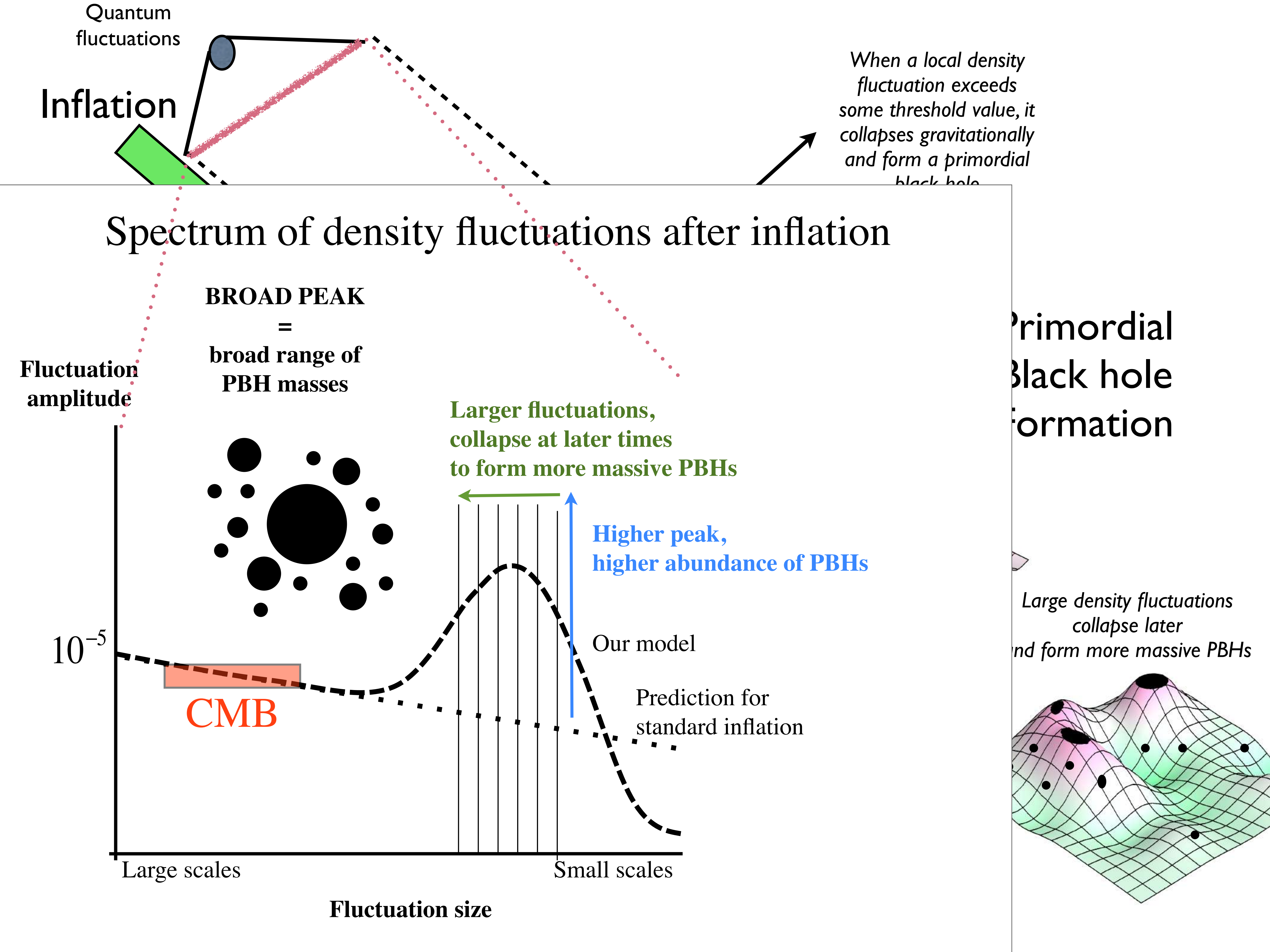

Quantum fluctuations
Inflation
Radiation era
When a local density fluctuation exceeds some threshold value, it collapses gravitationally and form a primordial black hole
Primordial Black hole Formation
Small-size density fluctuations collapse earlier and form less massive PBHs
Time evolution
Large density fluctuations collapse later and form more massive PBHs

Credit: Ilia Musco and Samuel Young



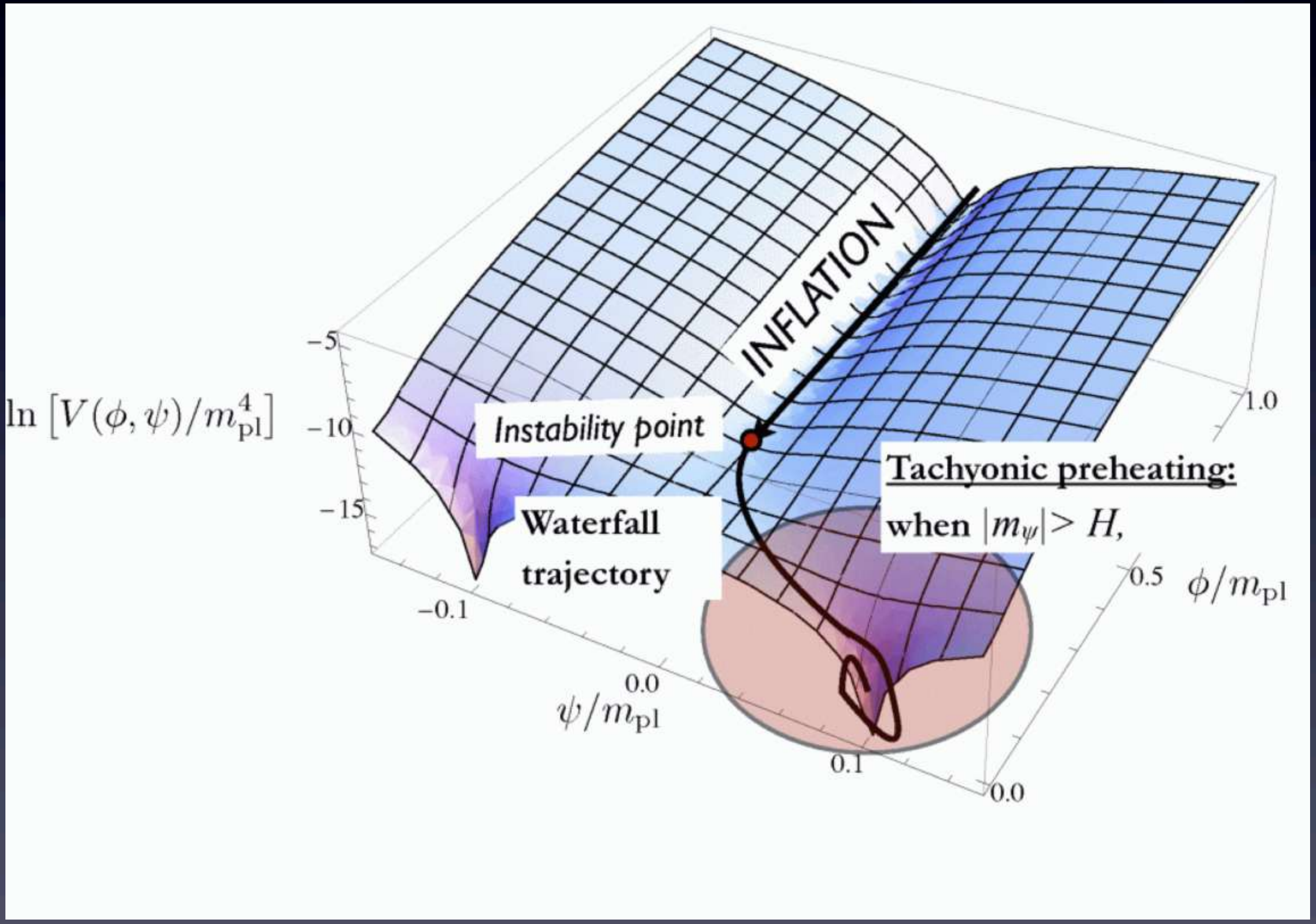





Quantum fluctuations
Inflation
When a local density fluctuation exceeds some threshold value, it collapses gravitationally and form a primordial black hole
Spectrum of density fluctuations after inflation
BROAD PEAK
=
broad range of PBH masses
Fluctuation amplitude
Larger fluctuations, collapse at later times to form more massive PBHs
Higher peak, higher abundance of PBHs
10^{-5}
Our model
Prediction for standard inflation
CMB
Large scales
Small scales
Fluctuation size
rimordial
lack hole
ormation
Large density fluctuations
collapse later
nd form more massive PBHs

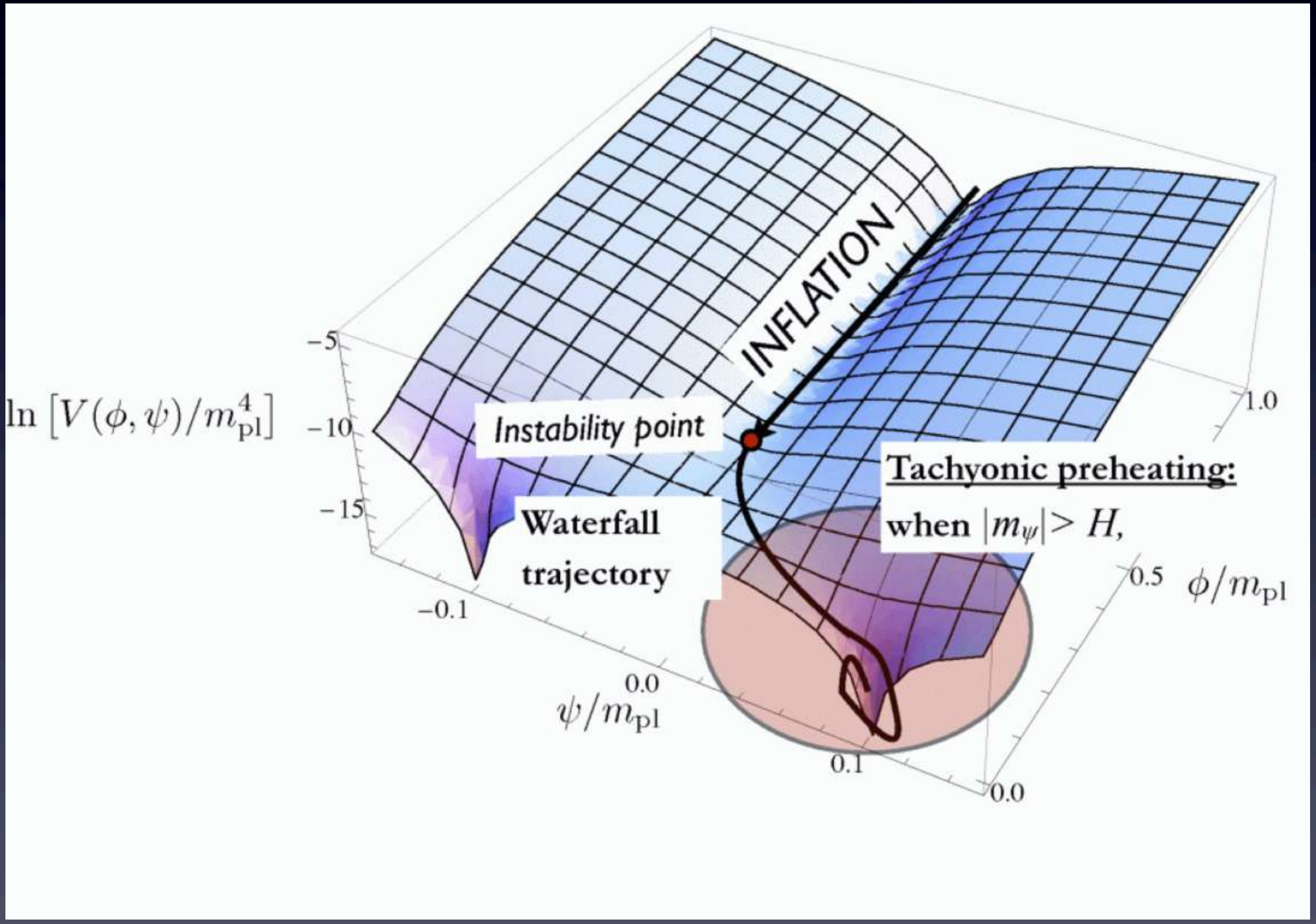
A formation model from Hybrid Inflation

It's like playing mini-golf... but the goal is to avoid the holes!



A formation model from Hybrid Inflation

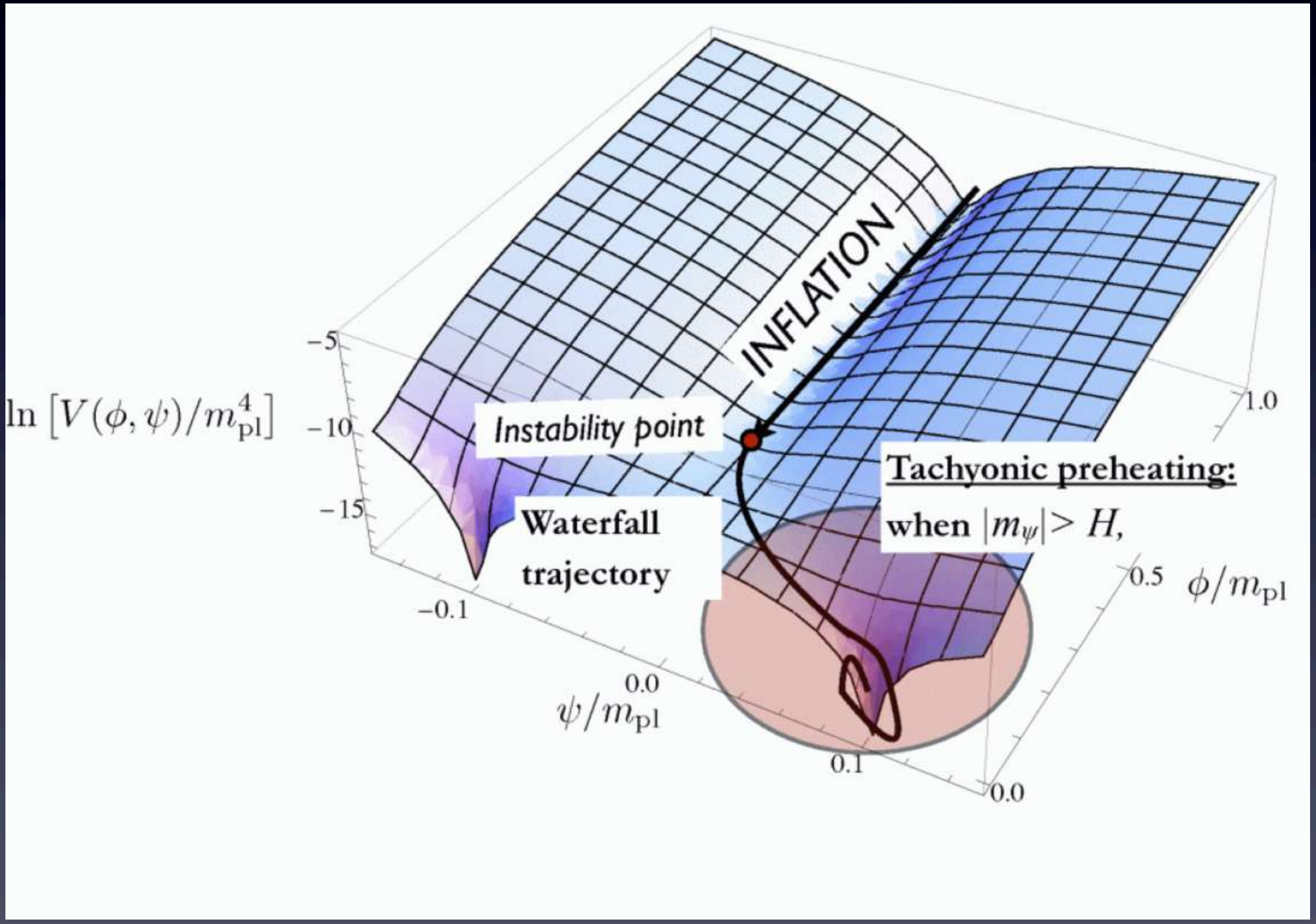
It's like playing mini-golf... but the goal is to avoid the holes!



- *Fast waterfall:* usual regime, less than 1-efold, disfavored

A formation model from Hybrid Inflation

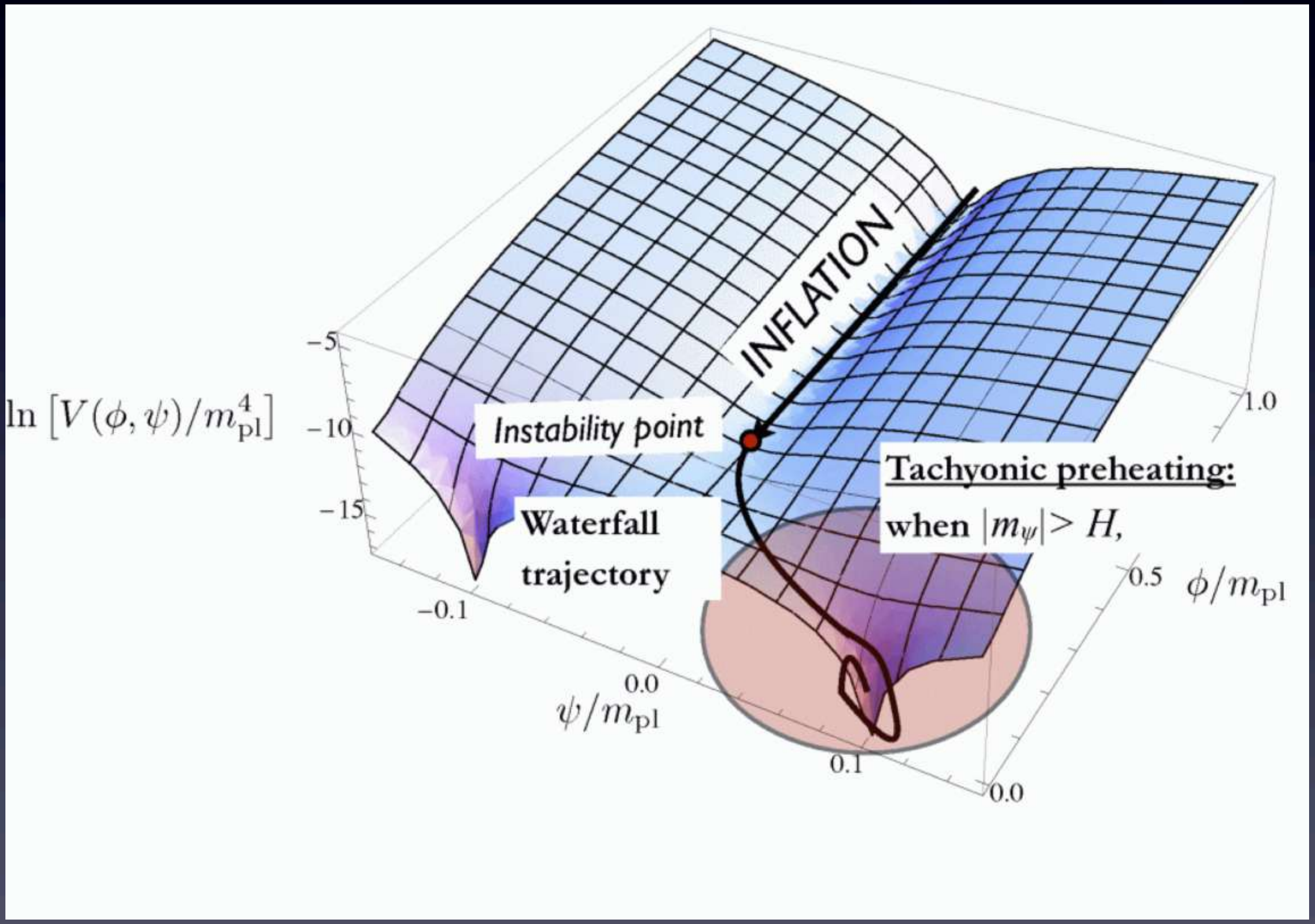
It's like playing mini-golf... but the goal is to avoid the holes!



- *Fast waterfall:* usual regime, less than 1-efold, disfavored
- *Mild waterfall:* *inflation continues (>60 e-folds),* ruled out

A formation model from Hybrid Inflation

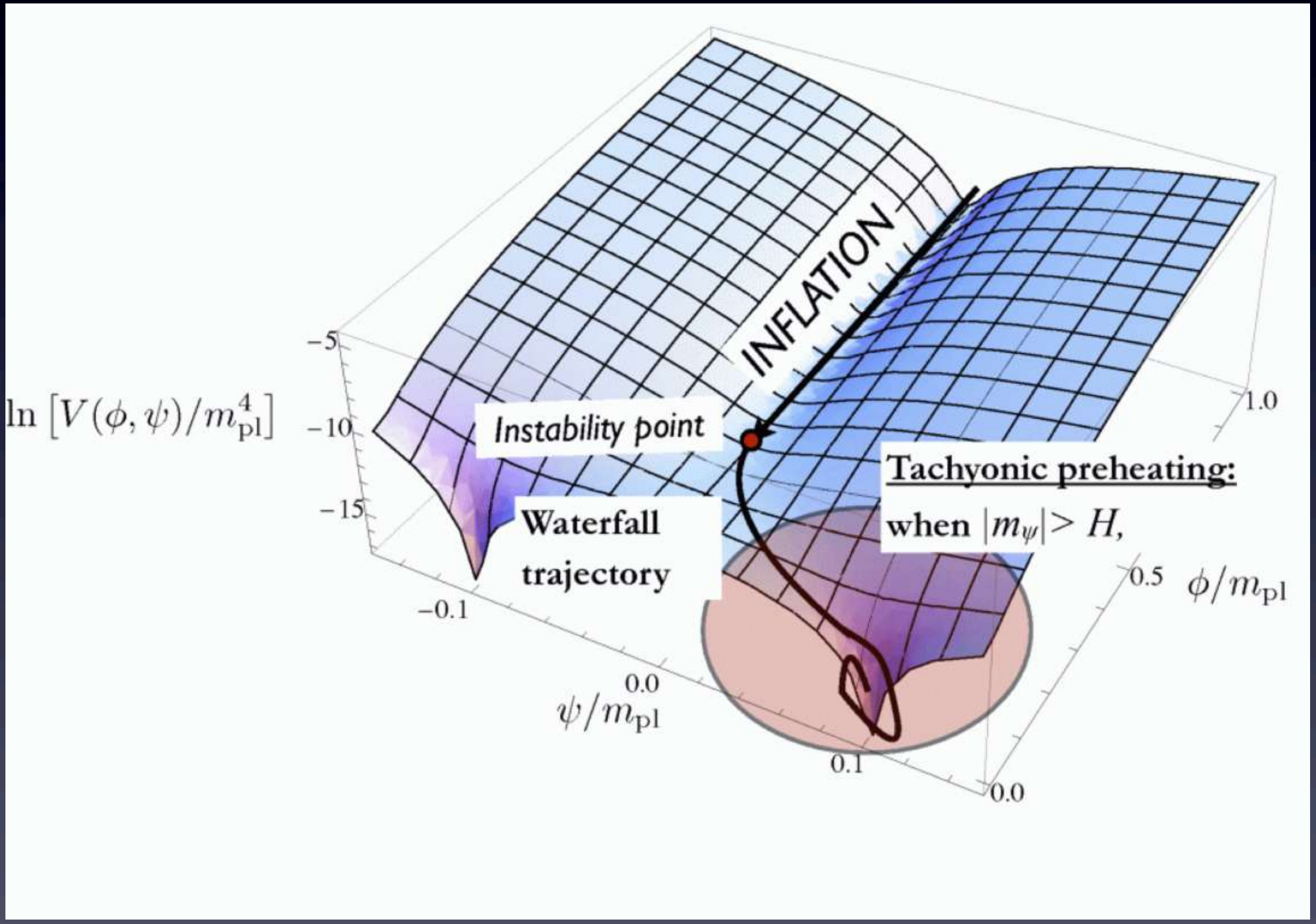
It's like playing mini-golf... but the goal is to avoid the holes!



- *Fast waterfall:* usual regime, less than 1-efold, disfavored
- *Mild waterfall: inflation continues (>60 e-folds),* ruled out
- *Transitory case:* a few tens of e-folds, CMB probes the valley

A formation model from Hybrid Inflation

It's like playing mini-golf... but the goal is to avoid the holes!

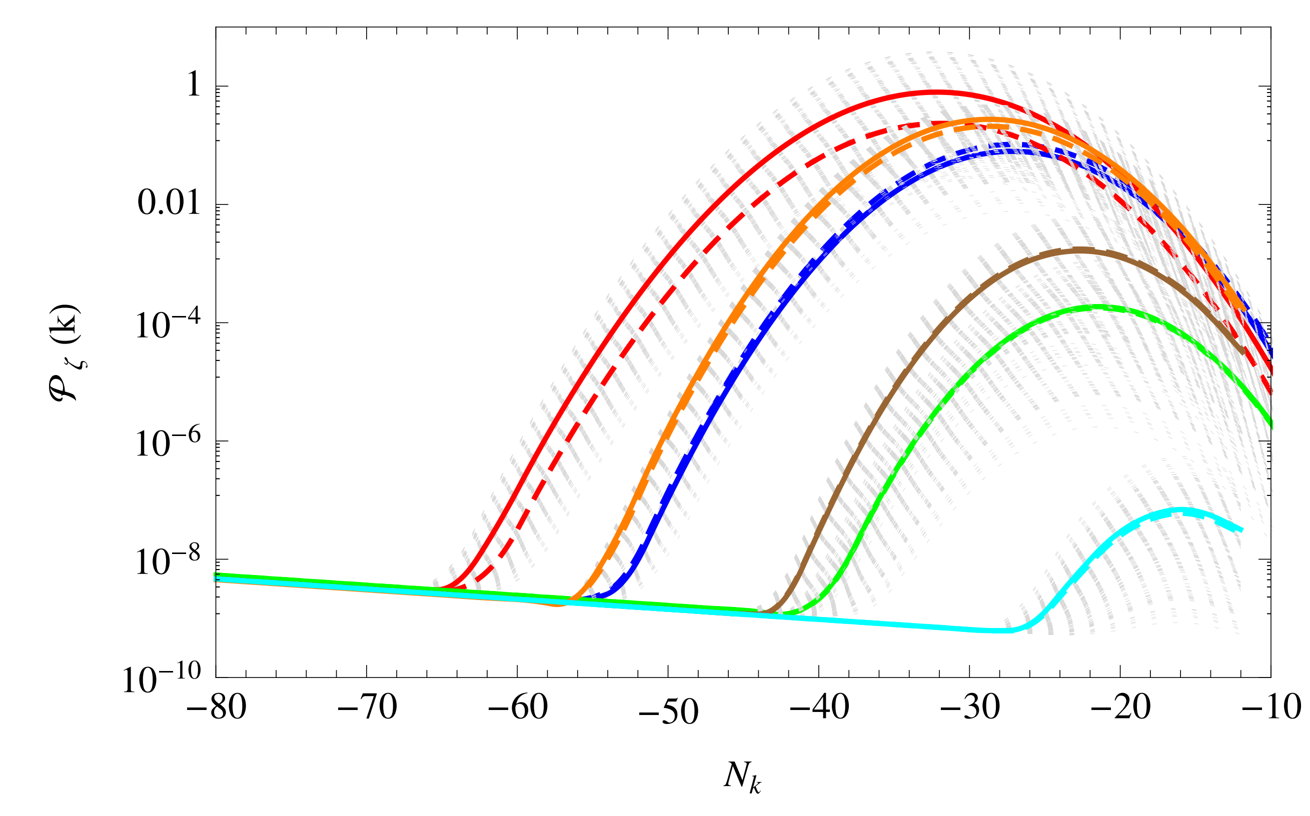


$$V(\phi,\psi) = \Lambda\left[\left(1-\frac{\psi^2}{M^2}\right)^2 + \frac{(\phi-\phi_{\rm c})}{\mu_1} - \frac{(\phi-\phi_{\rm c})^2}{\mu_2^2} + \frac{2\phi^2\psi^2}{M^2\phi_{\rm c}^2}\right]$$

Along $\psi = 0$, experts will recognize the first terms of a Taylor expansion of logarithmic radiative corrections (as in F-term, D-term, loop inflation)

A formation model from Hybrid Inflation

It's like playing mini-golf... but the goal is to avoid the holes!



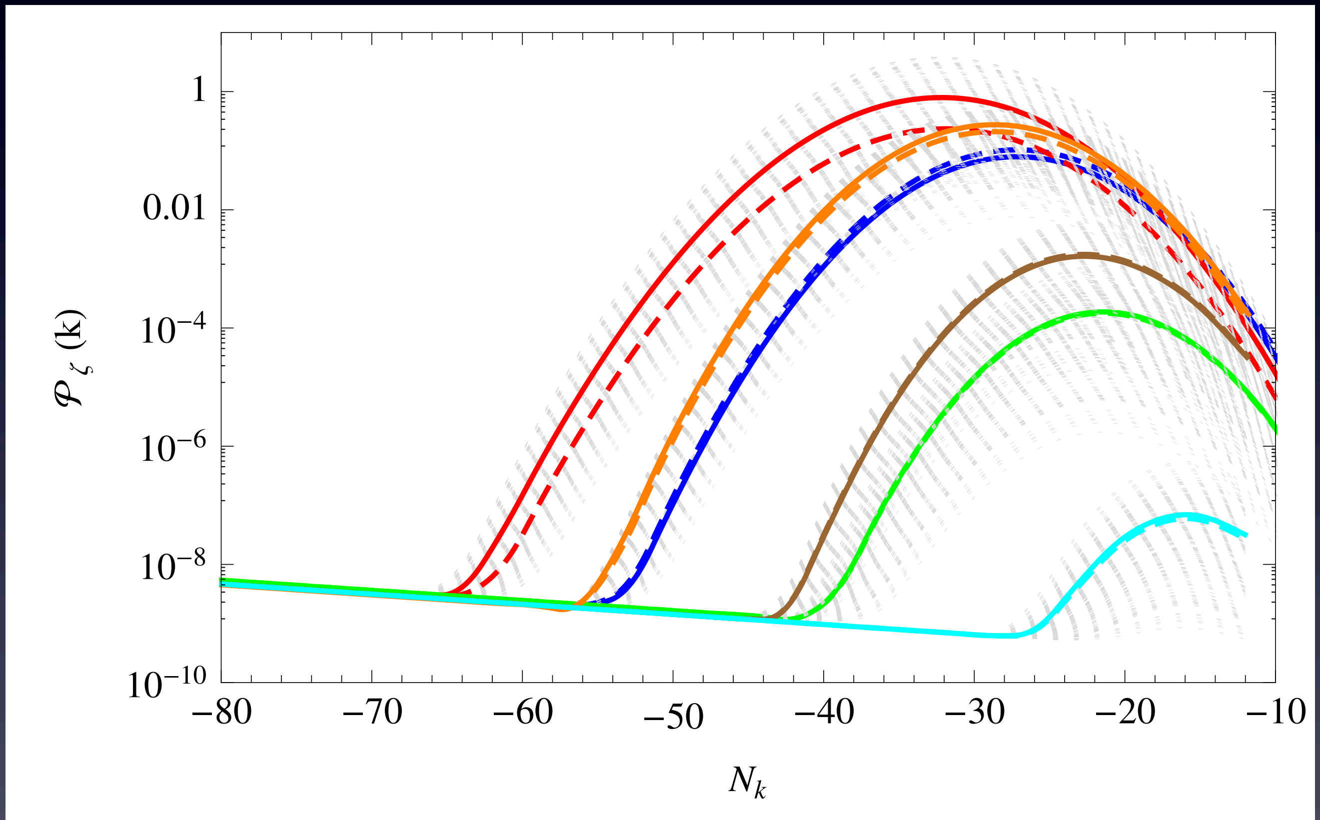
Primordial spectrum
of curvature fluctuations

Broad peak in the power spectrum
Position, width and amplitude fixed by $\Pi \equiv M\sqrt{\phi_c \mu_1}/M_{\rm pl}^2$

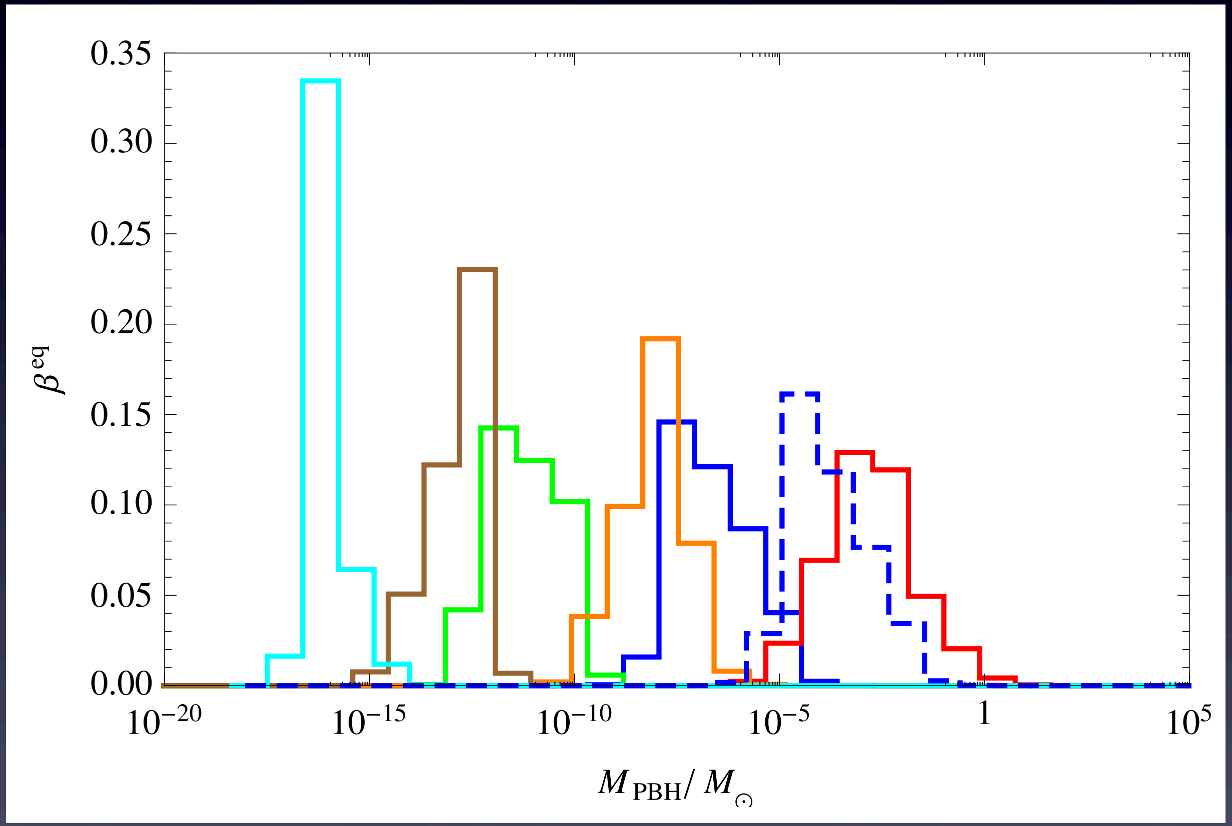
S.C. , J. Garcìa-Belldio, 1501.07565

A formation model from Hybrid Inflation

It's like playing mini-golf... but the goal is to avoid the holes!



Primordial spectrum of curvature fluctuations



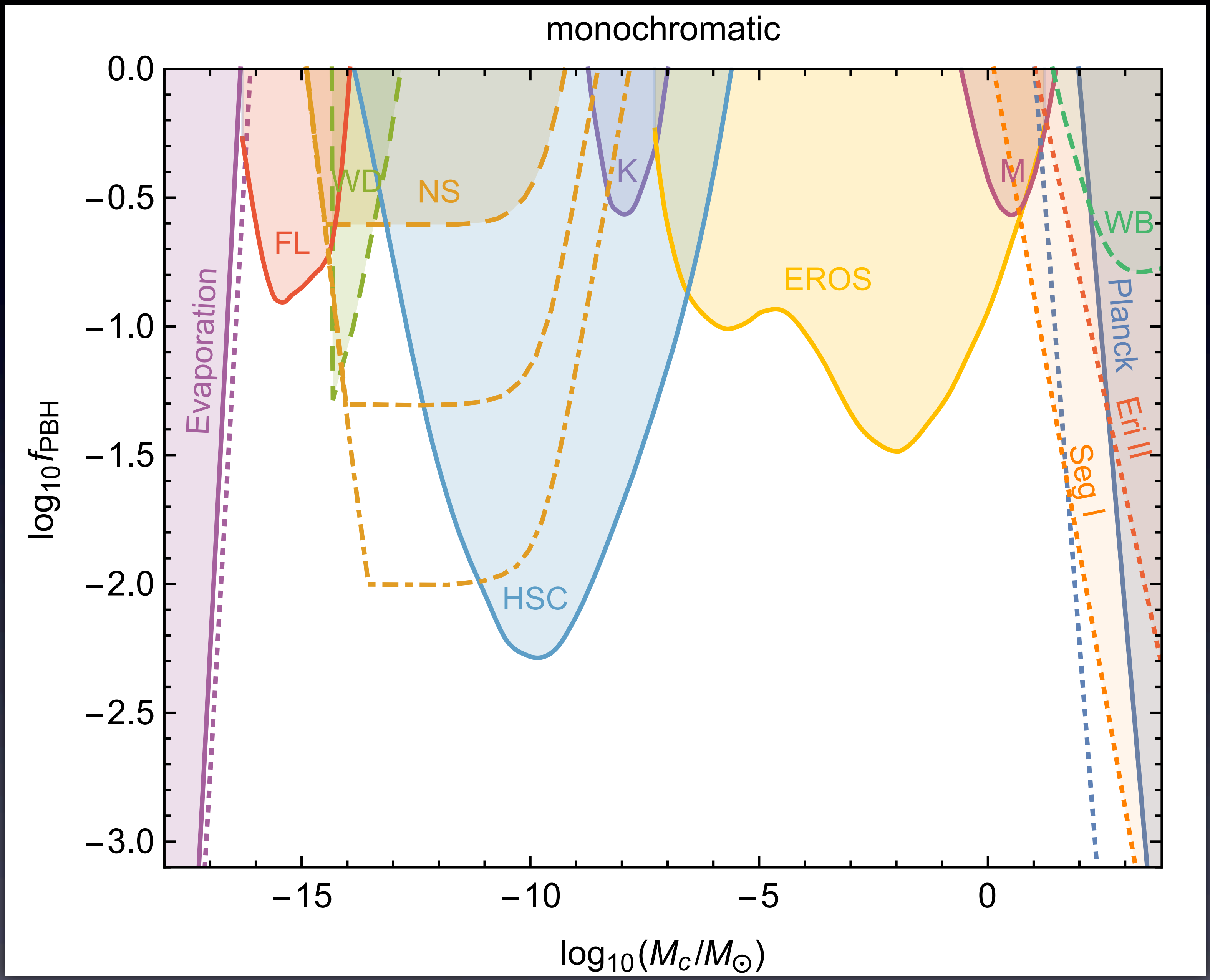
Collapsed fraction at the matter-radiation equality

Broad peak in the power spectrum
Position, width and amplitude fixed by $\Pi \equiv M\sqrt{\phi_c \mu_1}/M_{\rm pl}^2$

- **Surprisingly, reasonable values of $\zeta_c \rightarrow$ Dark Matter abundance**
- Relatively broad spectrum, PBH mass related to the parameter μ_1
- Open question: how efficient is PBH merging from this time?

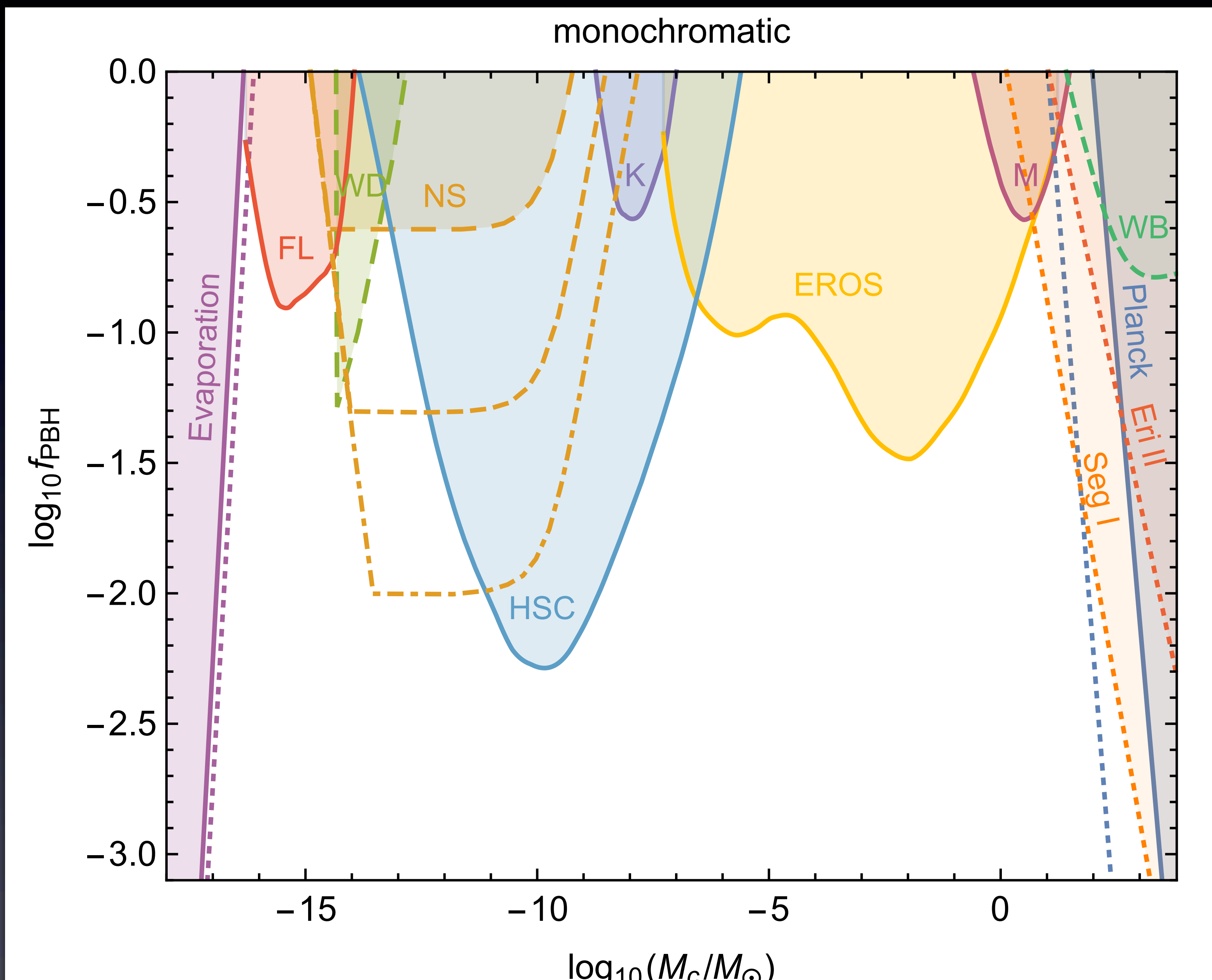
S.C. , J. Garcìa-Belldio, 1501.07565

Constraints on PBH abundances



B. Carr et al., 1705.05567

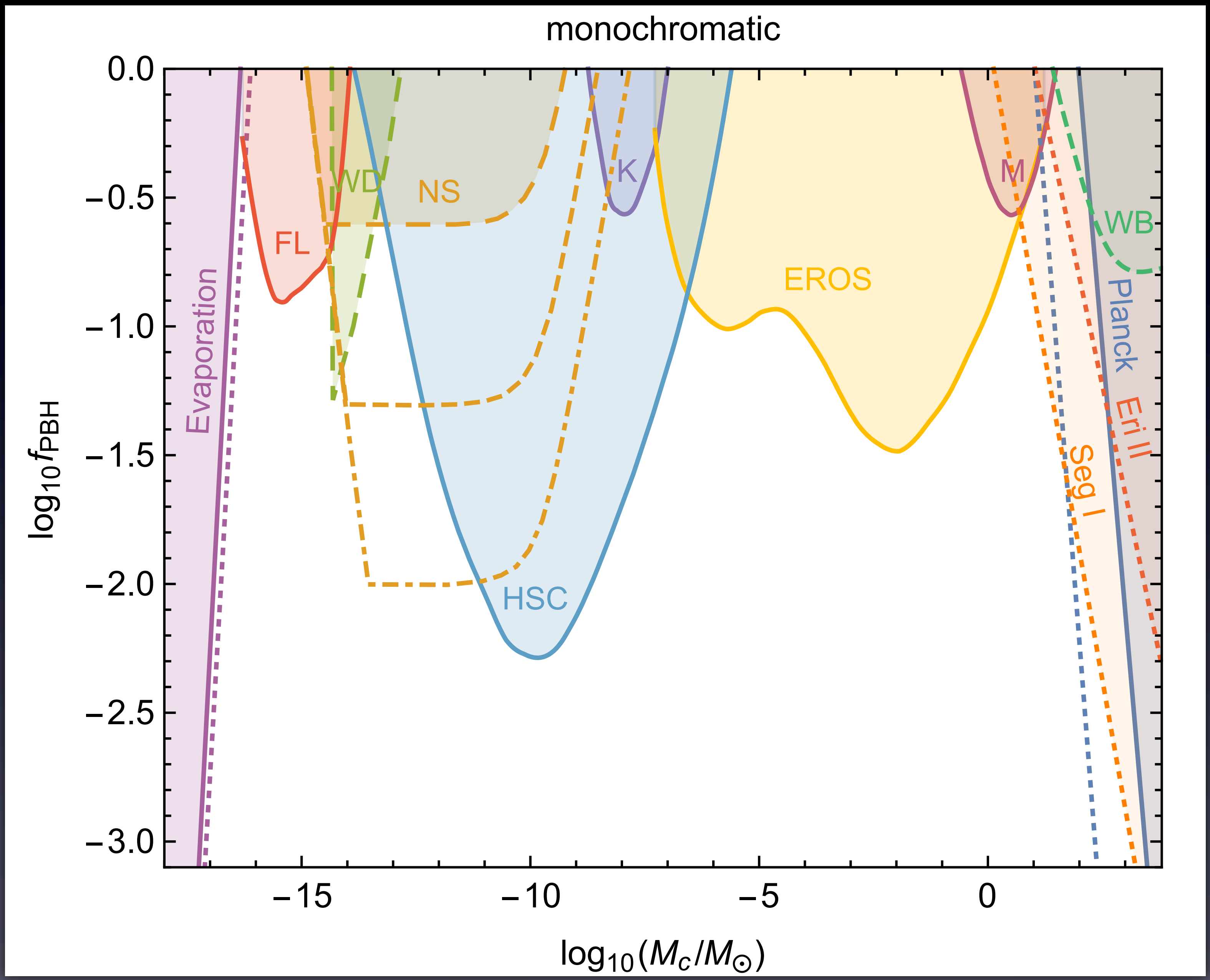
Constraints on PBH abundances



Monochromatic spectrum: PBH-DM looks excluded in the whole mass range

B. Carr et al., 1705.05567

Constraints on PBH abundances

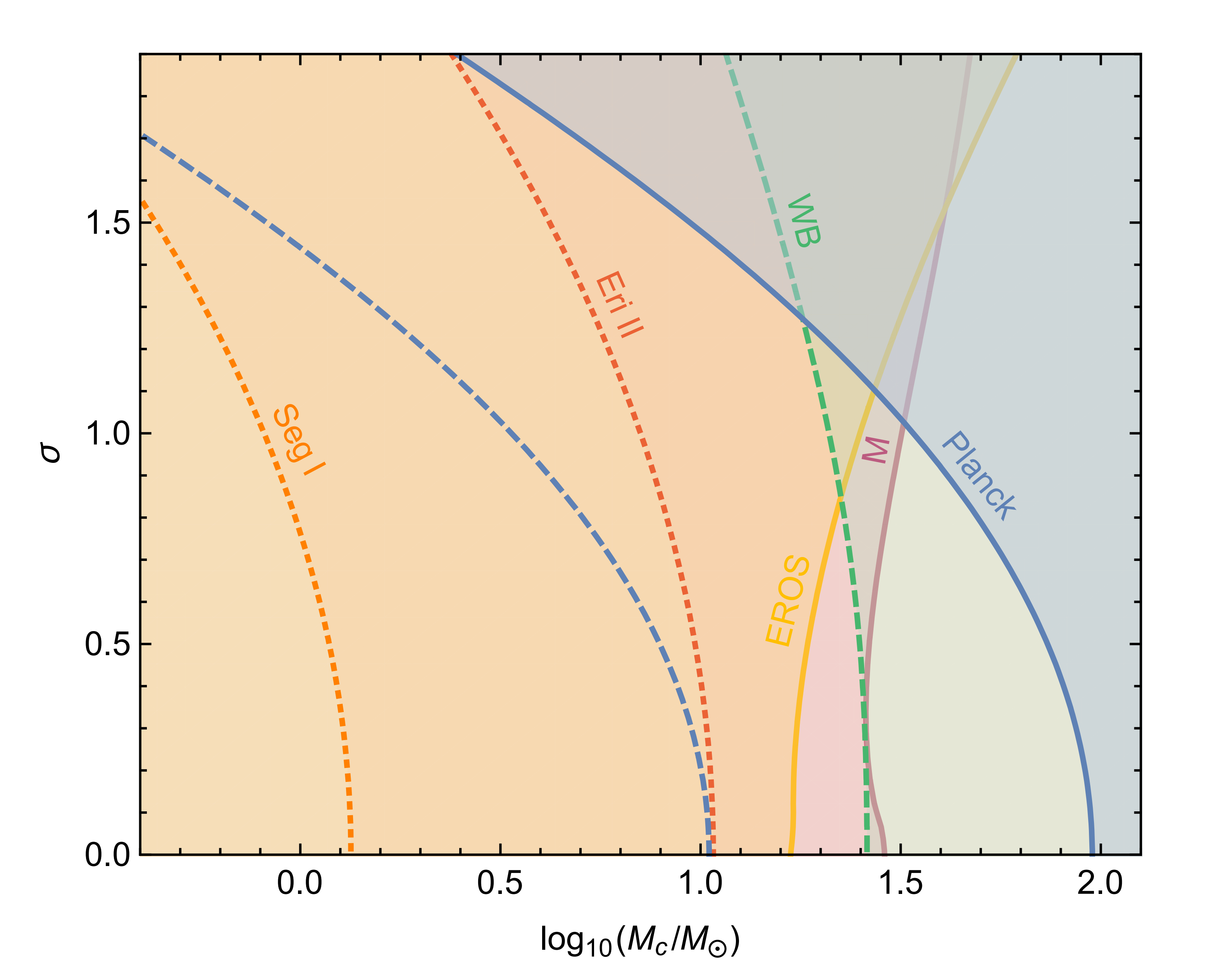


B. Carr et al., 1705.05567

Monochromatic spectrum:
PBH-DM looks excluded in the whole mass range

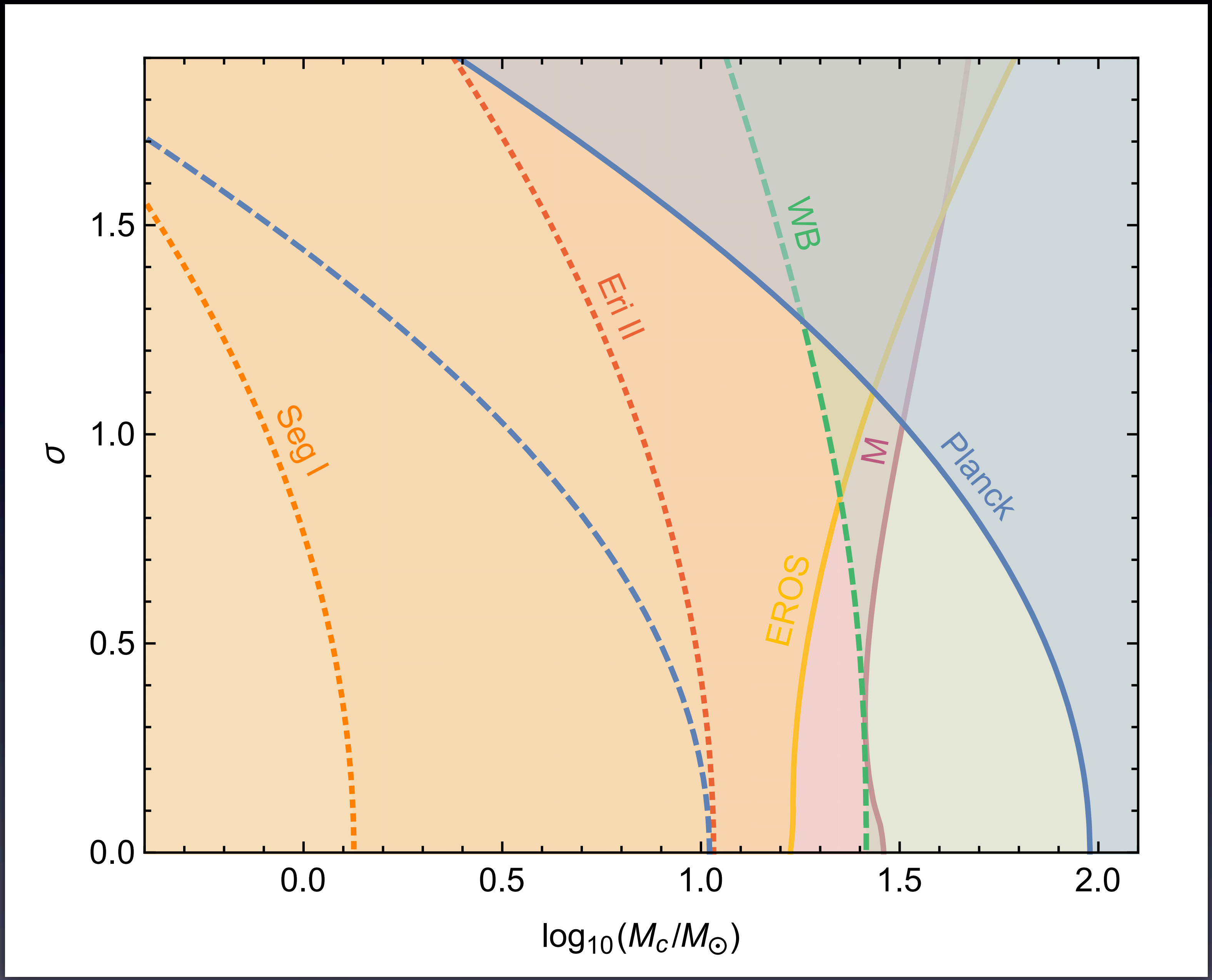
Microlensing constraints are controversial and change if PBH are clustered!
(SC., JGB, 1501.07565
A. Green, 1705.10818)!

Constraints on PBH abundances



B. Carr et al., 1705.05567

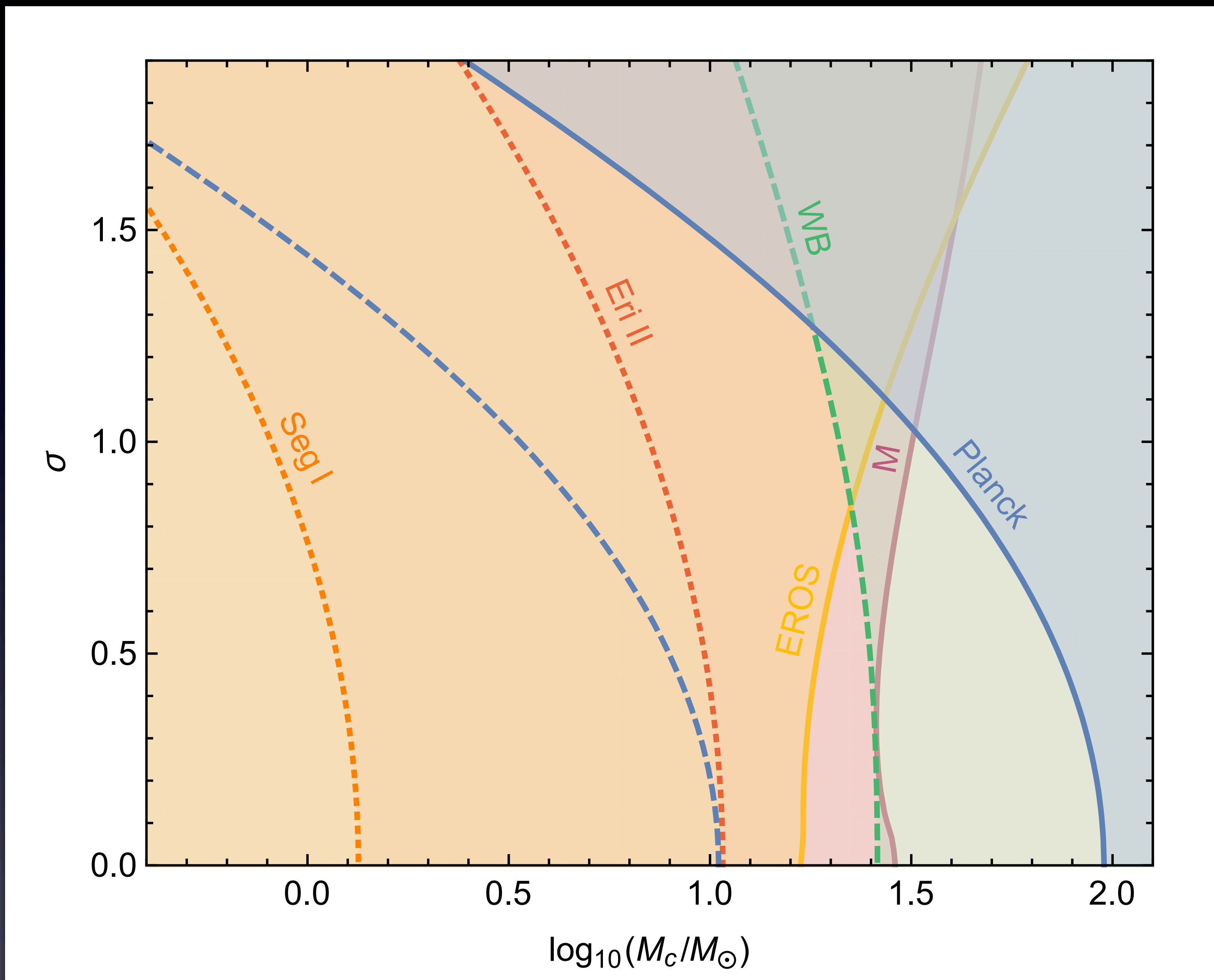
Constraints on PBH abundances



Broad spectrum (log-normal dist): PBH-DM looks excluded in the whole parameter range

B. Carr et al., 1705.05567

Constraints on PBH abundances

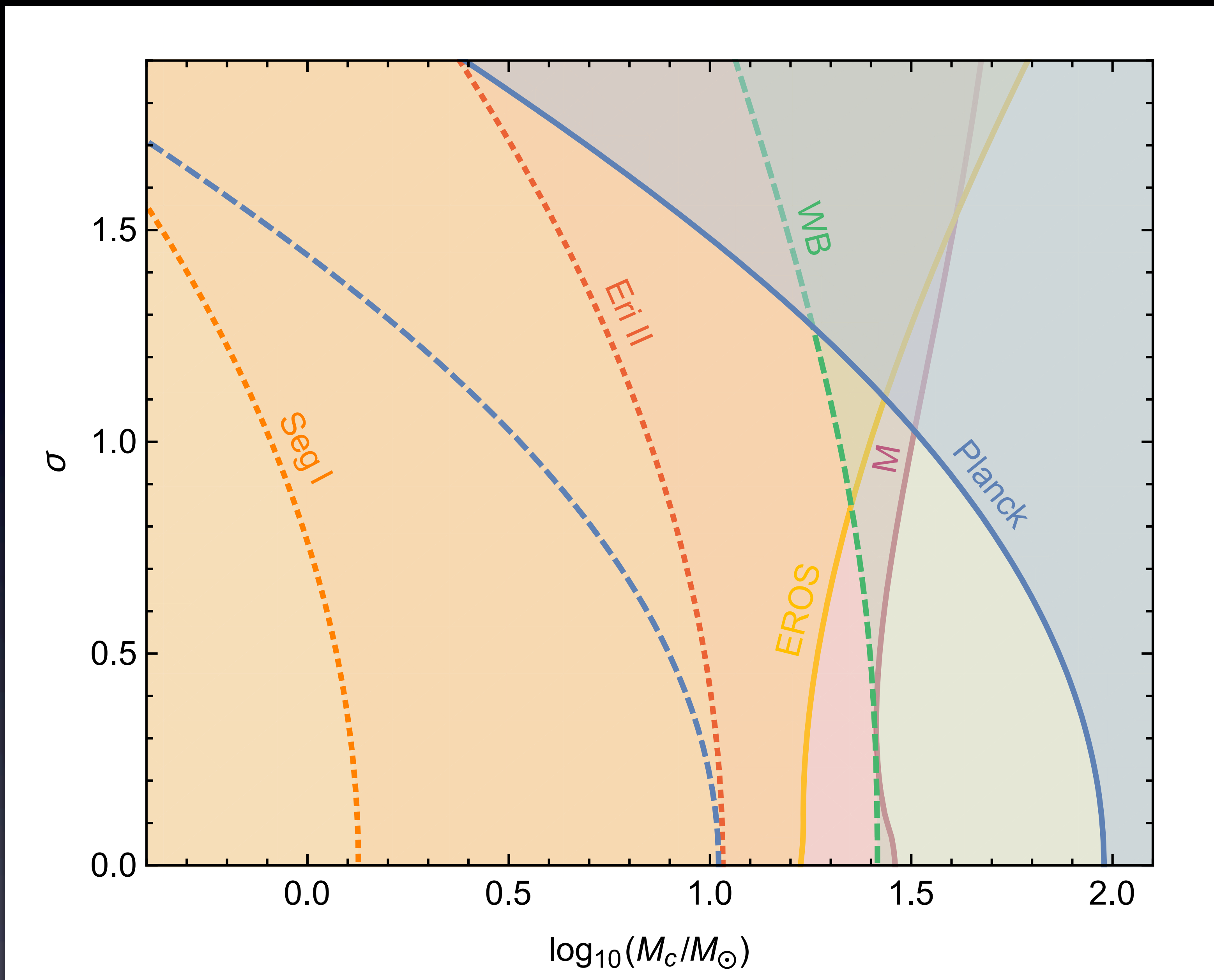


Broad spectrum (log-normal dist): PBH-DM looks excluded in the whole parameter range

Microlensing constraints controversial

B. Carr et al., 1705.05567

Constraints on PBH abundances



Broad spectrum (log-normal dist): PBH-DM looks excluded in the whole parameter range

Microlensing constraints controversial

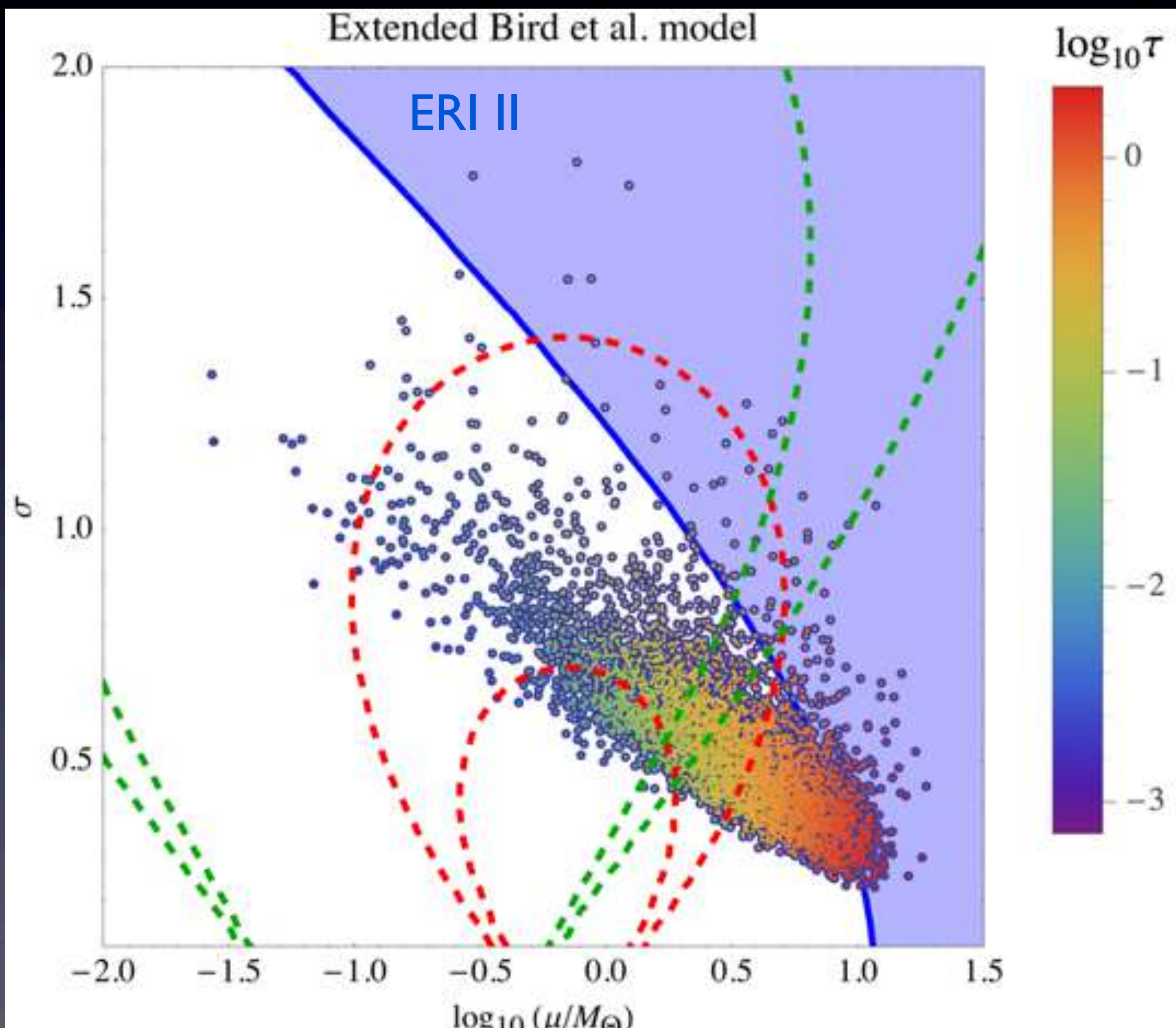
Segue 1 constraints cannot be simply extrapolated to the broad case

B. Carr et al., 1705.05567

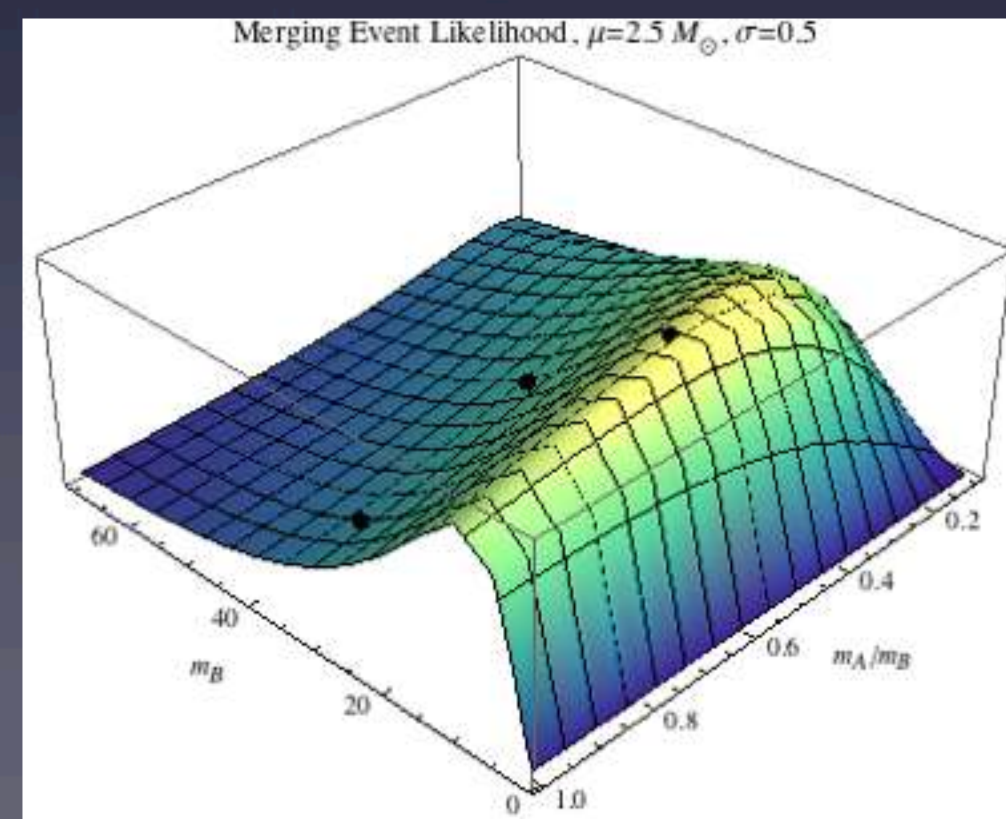
Five hints for PBH-DM

Five hints for PBH-DM

Hint 1: PBH rates and mass spectrum reconstruction

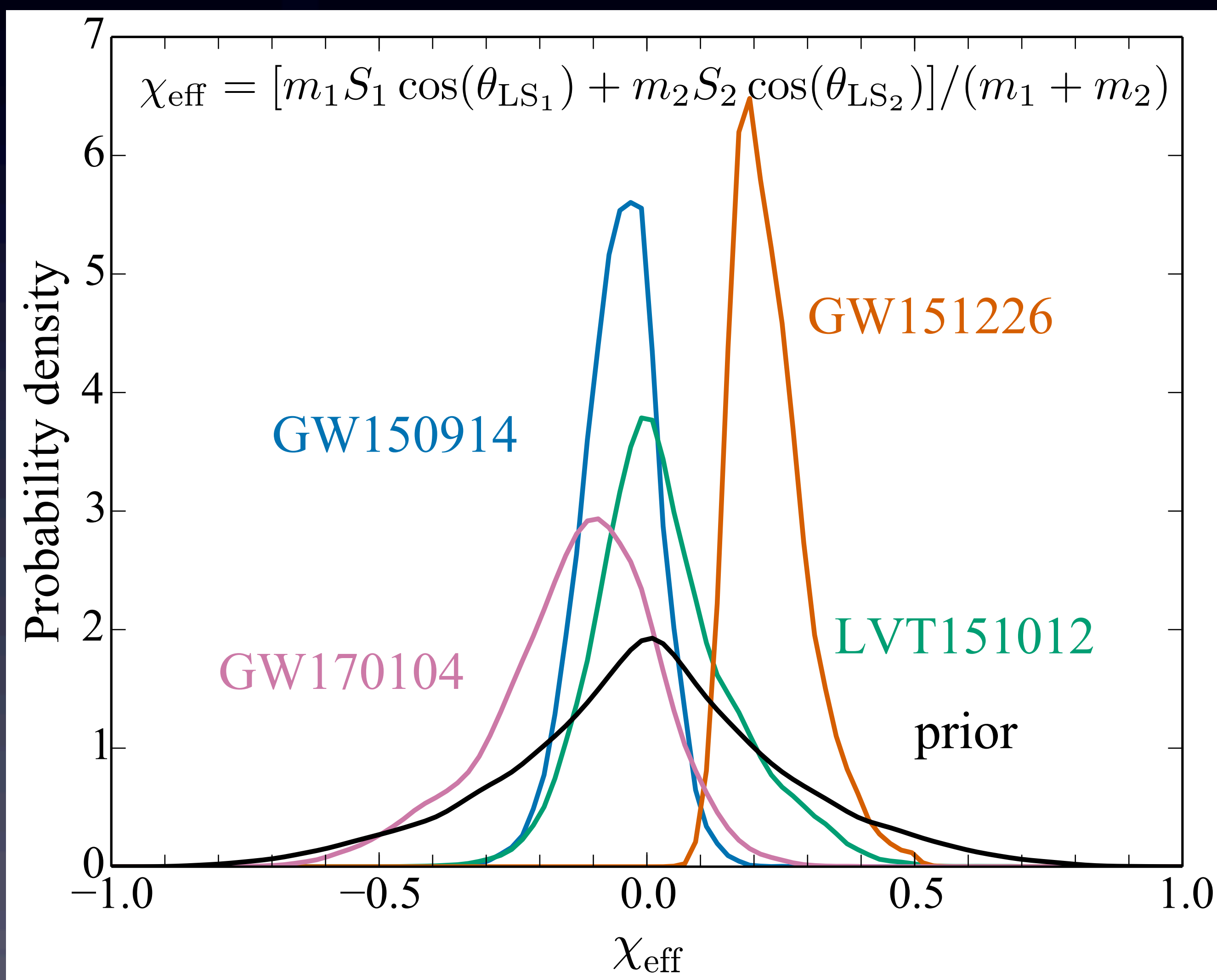


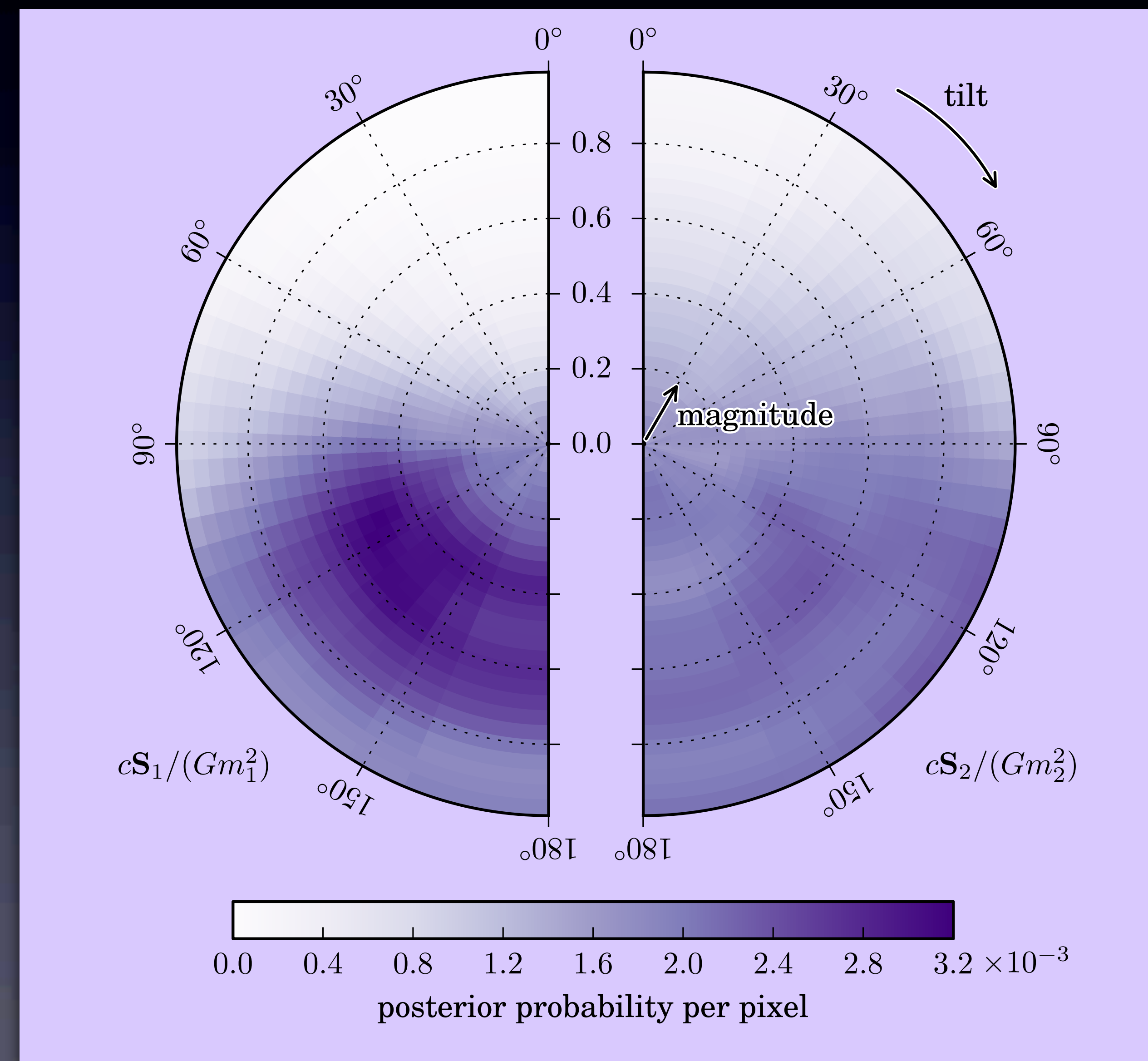
- MCMC mass spectrum reconstruction from LIGO events and rates
- Event likelihood peaks on large masses: LIGO detectability scales like inverse distance



Five hints for PBH-DM

Hint 2: Black Hole spins



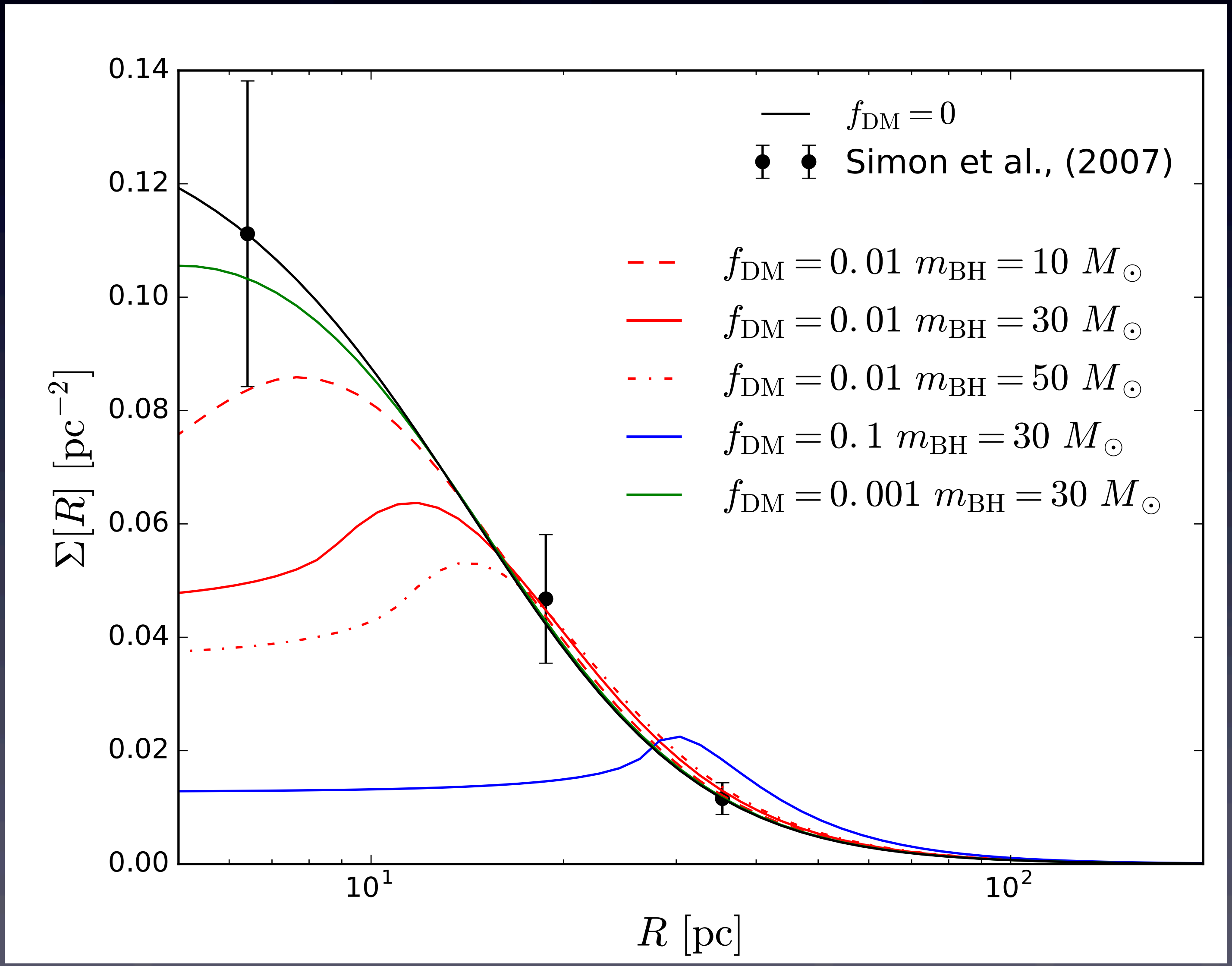


Point towards a capture process and relatively low spins

Five hints for PBH-DM

Hint 3: Star clusters in faint dwarf galaxies

- If most PBHs have stellar masses, dynamical heating is naturally reduced
- On the other hand, the existence of stable star clusters is fine-tuned for particle dark matter: Amorisco 1704.06262
- Star survival in ERI II cluster challenge particle dark matter: Contena et al, 1705.01820
- Re-analysis and N-body simulations in progress...

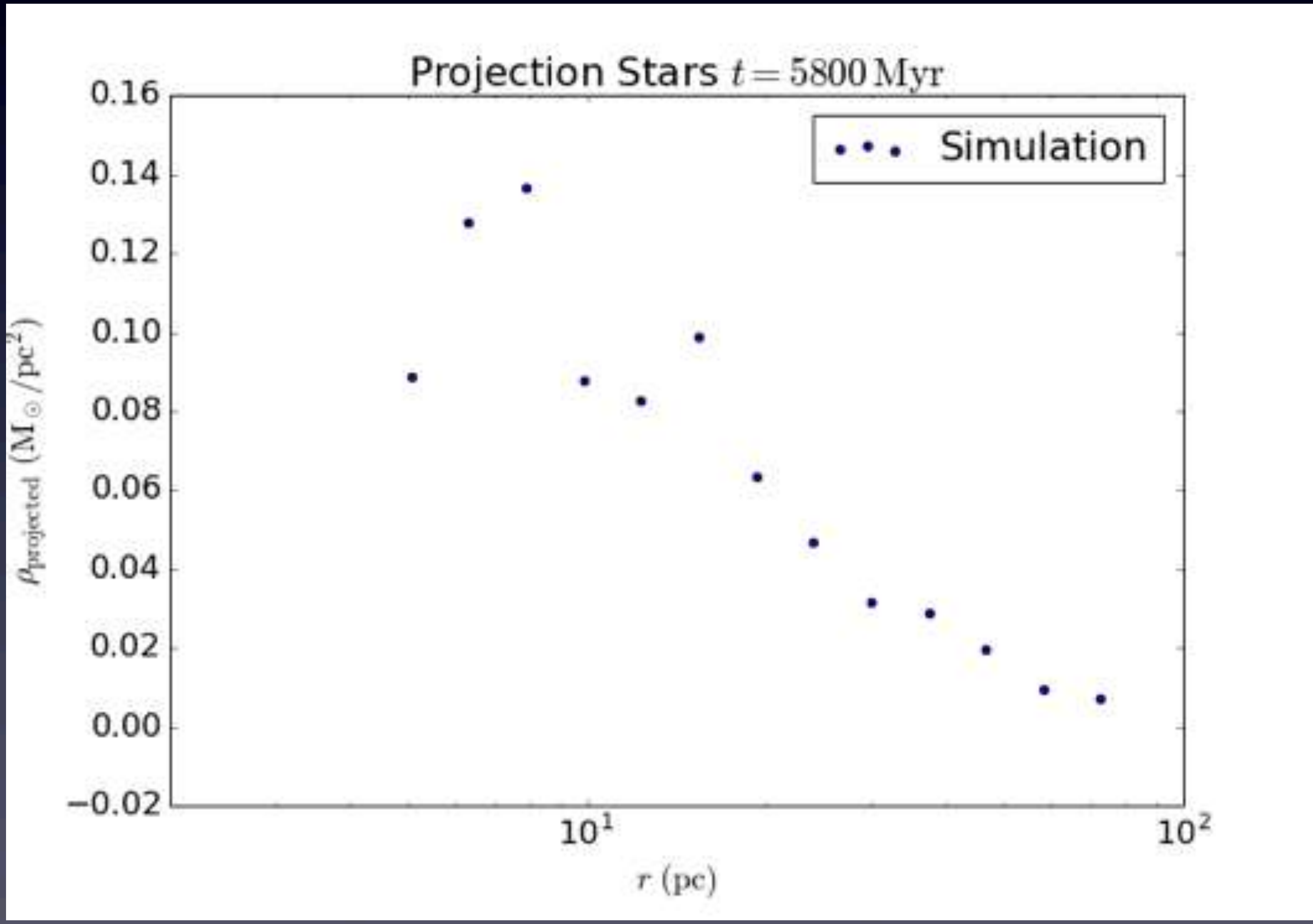


Segue 1 projected surface density, Koushiappas & Loeb, 1704.01668

Five hints for PBH-DM

Hint 3: Star clusters in faint dwarf galaxies

- If most PBHs have stellar masses, dynamical heating is naturally reduced
- On the other hand, the existence of stable star clusters is fine-tuned for particle dark matter: Amorisco 1704.06262
- Star survival in ERI II cluster challenge particle dark matter: Contena et al, 1705.01820
- Re-analysis and N-body simulations in progress...

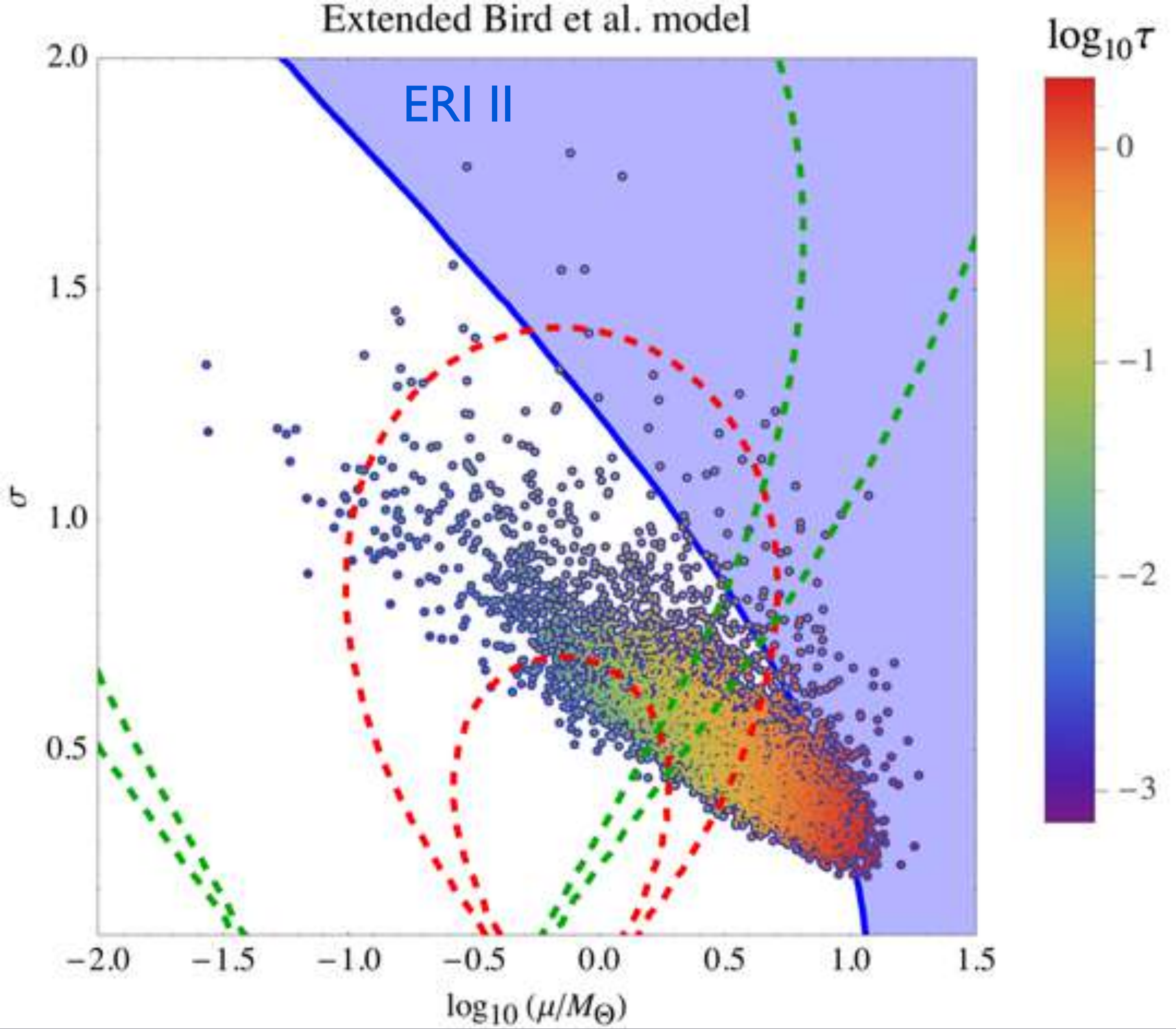


N-body sims,
thanks to Markus Schmidt

Five hints for PBH-DM

Hint 4: Microlensing of M31 and quasars

- 56 microlensing events in M31: between 15% and 30% of halo compact objects in range [0.5-1] Msun (1504.07246)
- 24 micro-lensing of quasars by galaxies: between 15% and 25% of halo compact objects in range [0.05-0.45] Msun (1702.00947)
- Also in Magellanic cloud surveys, but still controversial

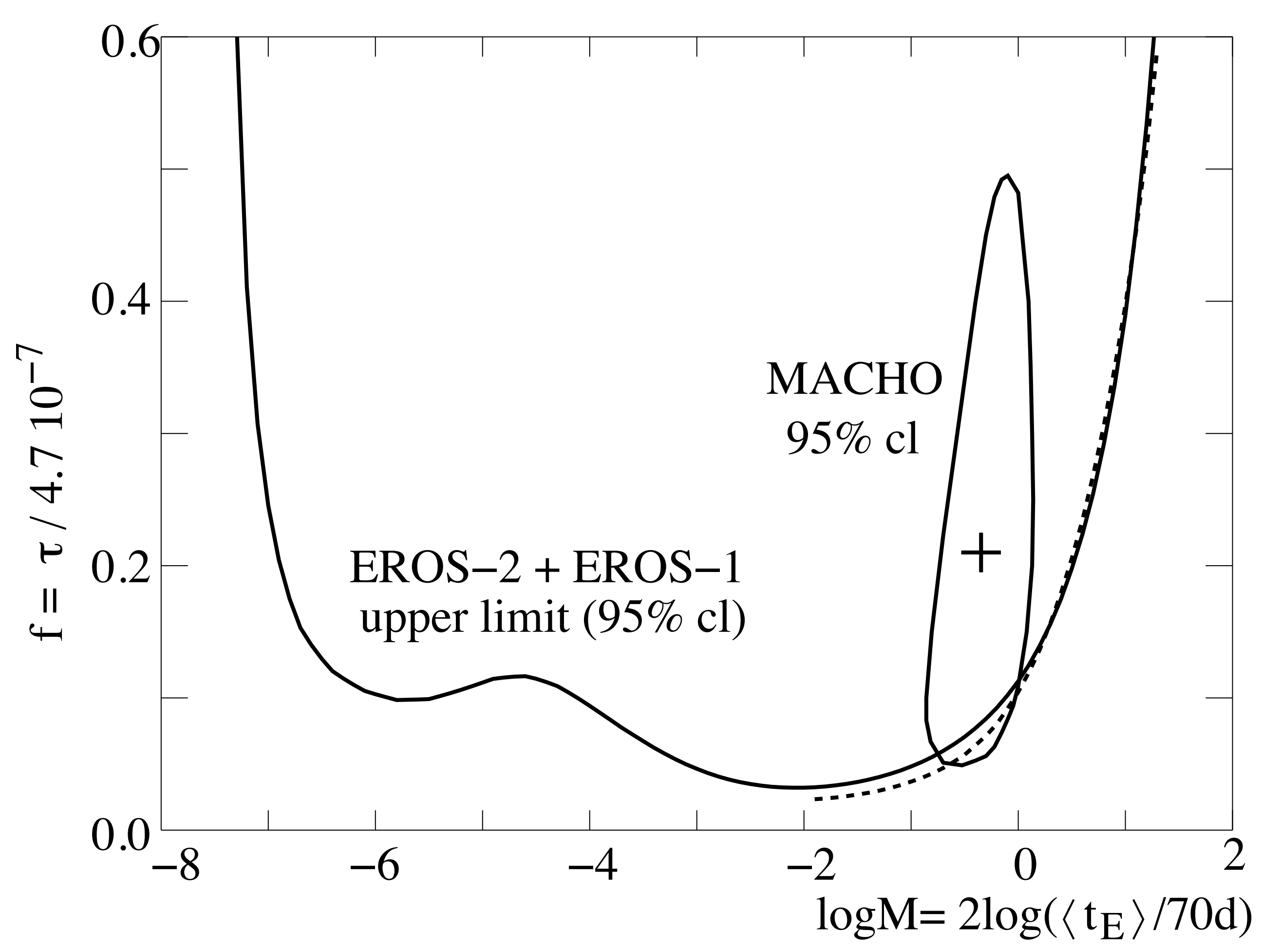


Five hints for PBH-DM

Hint 4: Microlensing of M31 and quasars

- 56 microlensing events in M31: between 15% and 30% of halo compact objects in range [0.5-1] Msun (1504.07246)
- 24 micro-lensing of quasars by galaxies: between 15% and 25% of halo compact objects in range [0.05-0.45] Msun (1702.00947)
- Also in Magellanic cloud surveys, but still controversial

EROS vs MACHO (astro-ph/0607207)



Five hints for PBH-DM

Hint 5: Spatial correlations in CIB and X-ray background

LIGO gravitational wave detection, primordial black holes and the near-I cosmic infrared background anisotropies

A. Kashlinsky[1],

ABSTRACT

LIGO's discovery of a gravitational wave from two merging black holes (BHs) of similar masses rekindled suggestions that primordial BHs (PBHs) make up the dark matter (DM). If so, PBHs would add a Poissonian isocurvature density fluctuation component to the inflation-produced adiabatic density fluctuations. For LIGO's BH parameters, this extra component would dominate the small-scale power responsible for collapse of early DM halos at $z \gtrsim 10$, where first luminous sources formed. We quantify the resultant increase in high-z abundances of collapsed halos that are suitable for producing the first generation of stars and luminous sources. The significantly increased abundance of the early halos would naturally explain the observed source-subtracted near-IR cosmic infrared background (CIB) fluctuations, which cannot be accounted for by known galaxy populations. For LIGO's BH parameters this increase is such that the observed CIB fluctuation levels at 2 to 5 μm can be produced if only a tiny fraction of baryons in the collapsed DM halos forms luminous sources. Gas accretion onto these PBHs in collapsed halos, where first stars should also form, would straightforwardly account for the observed high coherence between the CIB and unresolved cosmic X-ray background in soft X-rays. We discuss modifications possibly required in the processes of first star formation if LIGO-type BHs indeed make up the bulk or all of DM. The arguments are valid only if the PBHs make up all, or at least most, of DM, but at the same time the mechanism appears inevitable if DM is made of PBHs.

1605.04023

Pros & Cons...

Primordial Black holes with a broad (σ~0.5-0.8) mass spectrum centered on μ~1-5 Msun

- LIGO merging rates and BH masses
- LIGO BH spins
- M31 & quasar microlensing
- Star cluster and stability of faint dwarf galaxies
- Spatial correlations between CIB and X-ray backgrounds

Pros & Cons...

Primordial Black holes with a broad (σ~0.5-0.8) mass spectrum centered on μ~1-5 Msun

- LIGO merging rates and BH masses
- LIGO BH spins
- M31 & quasar microlensing
- Star cluster and stability of faint dwarf galaxies
- Spatial correlations between CIB and X-ray backgrounds
- Pass all the other observational constraints

Pros & Cons...

Primordial Black holes with a broad (σ~0.5-0.8) mass spectrum centered on μ~1-5 Msun

- LIGO merging rates and BH masses
- LIGO BH spins
- M31 & quasar microlensing
- Star cluster and stability of faint dwarf galaxies
- Spatial correlations between CIB and X-ray backgrounds
- Pass all the other observational constraints
- Provide seeds for SMBH in the queue of the spectrum

Pros & Cons...

Primordial Black holes with a broad (σ~0.5-0.8) mass spectrum centered on μ~1-5 Msun

- LIGO merging rates and BH masses
- LIGO BH spins
- M31 & quasar microlensing
- Star cluster and stability of faint dwarf galaxies
- Spatial correlations between CIB and X-ray backgrounds
- Pass all the other observational constraints
- Provide seeds for SMBH in the queue of the spectrum
- Provide a solution to the too-big-to-fail and dwarf satellite problems

Pros & Cons...

Primordial Black holes with
a broad (σ~0.5-0.8) mass spectrum centered on μ~1-5 Msun

- No clear observational evidence (yet?)
- Why the mean PBH mass coincides with the BH mass from star evolution
(Fine-tuning? Formation mechanism? Other?)
- Inconsistent merging rates if the model by Sasaki et al. is correct

...and future prospects

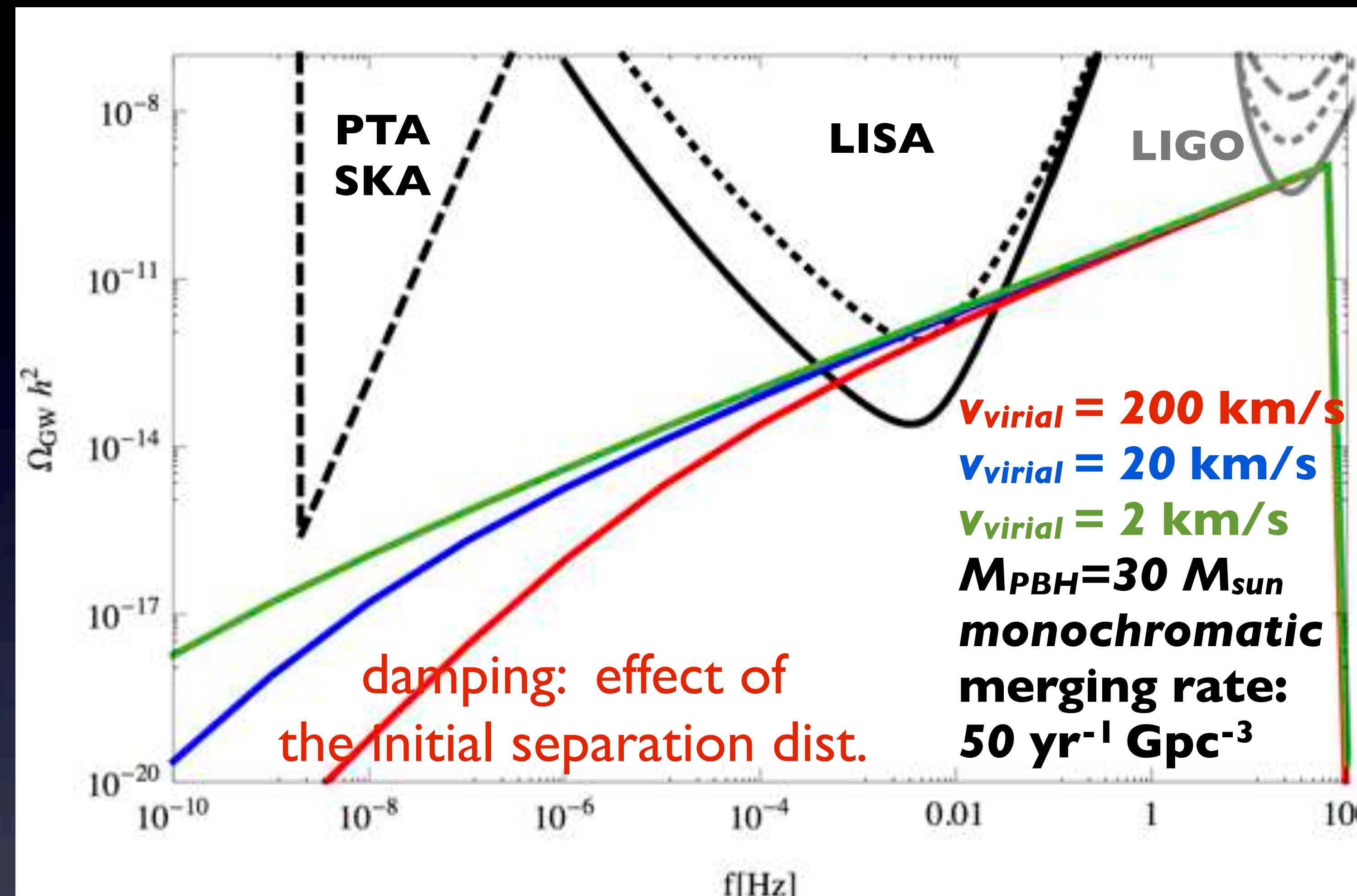
- Detecting a BH below the Chandrashekar mass (LIGO)
- Numerous merging events seen in GW detectors (LIGO, VIRGO, ET...)
- GW Stochastic Background (PTAs, LISA, LIGO)
- Detecting faint dwarf galaxies (DES, Euclid)
- Microlensing surveys (Euclid)
- 21cm signal (SKA)
- CMB distortions (PIXIE)
- Star position and velocities (GAIA)

...and future prospects

- Detecting a BH below the Chandrashekar mass (LIGO)
- Numerous merging events seen in GW detectors (LIGO, VIRGO, ET...)
- GW Stochastic Background (PTAs, LISA, LIGO)
- Detecting faint dwarf galaxies (DES, Euclid)
- Microlensing surveys (Euclid)
- 21cm signal (SKA)
- CMB distortions (PIXIE)
- Star position and velocities (GAIA)

...and future prospects

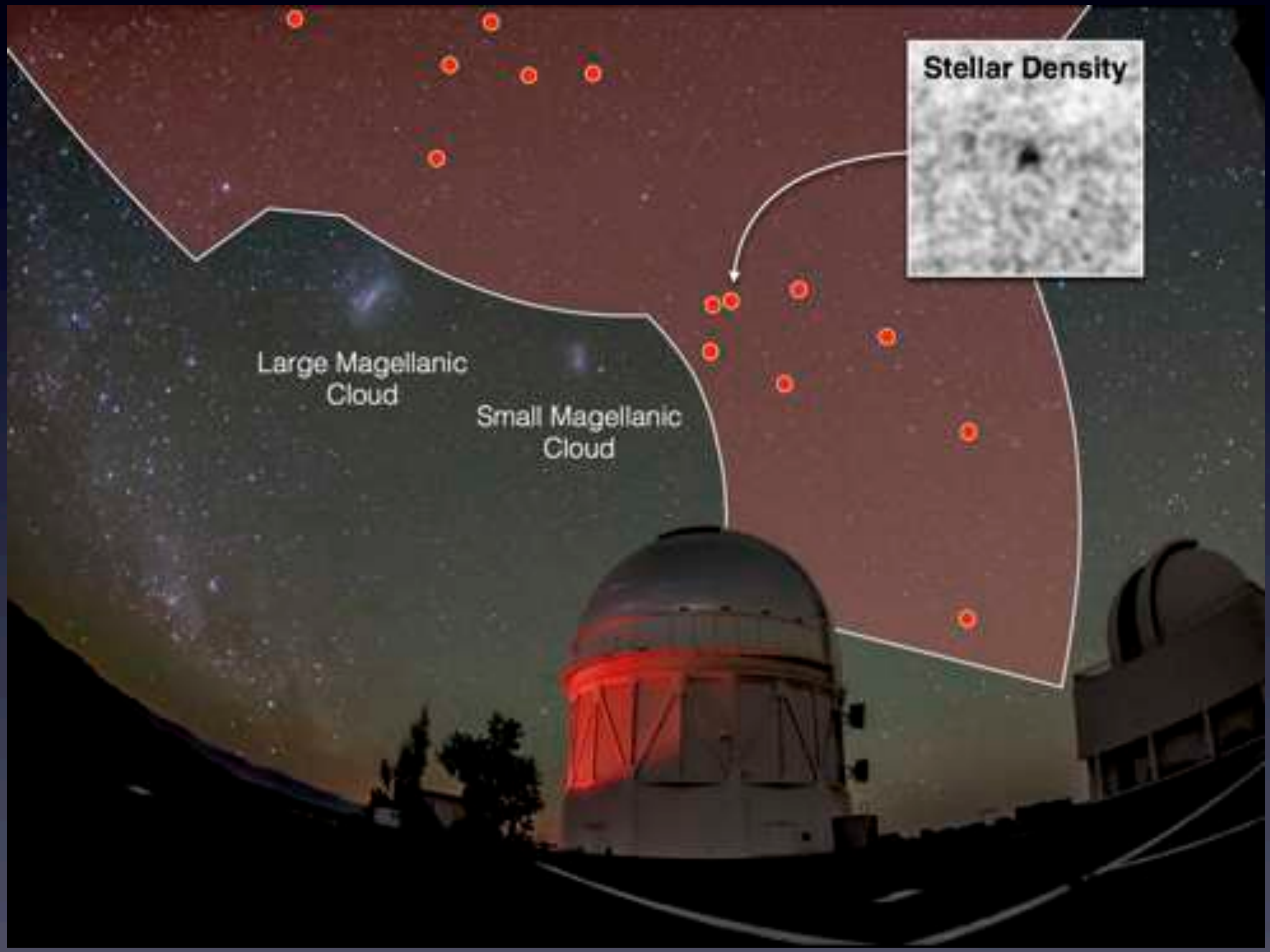
- Detecting a BH below the Chandrashekar mass (LIGO)
- Numerous merging events seen in GW detectors (LIGO, VIRGO, ET...)
- GW Stochastic Background (PTAs, LISA, LIGO)
- Detecting faint dwarf galaxies (DES, Euclid)
- Microlensing surveys (Euclid)
- 21cm signal (SKA)
- CMB distortions (PIXIE)
- Star position and velocities (GAIA)



Clustering allows to distinguish stellar and primordial origins
SC, JGB, 1610.08479

...and future prospects

- Detecting a BH below the Chandrashekar mass (LIGO)
- Numerous merging events seen in GW detectors (LIGO, VIRGO, ET...)
- GW Stochastic Background (PTAs, LISA, LIGO)
- Detecting faint dwarf galaxies (DES, Euclid)
- Microlensing surveys (Euclid)
- 21cm signal (SKA)
- CMB distortions (PIXIE)
- Star position and velocities (GAIA)

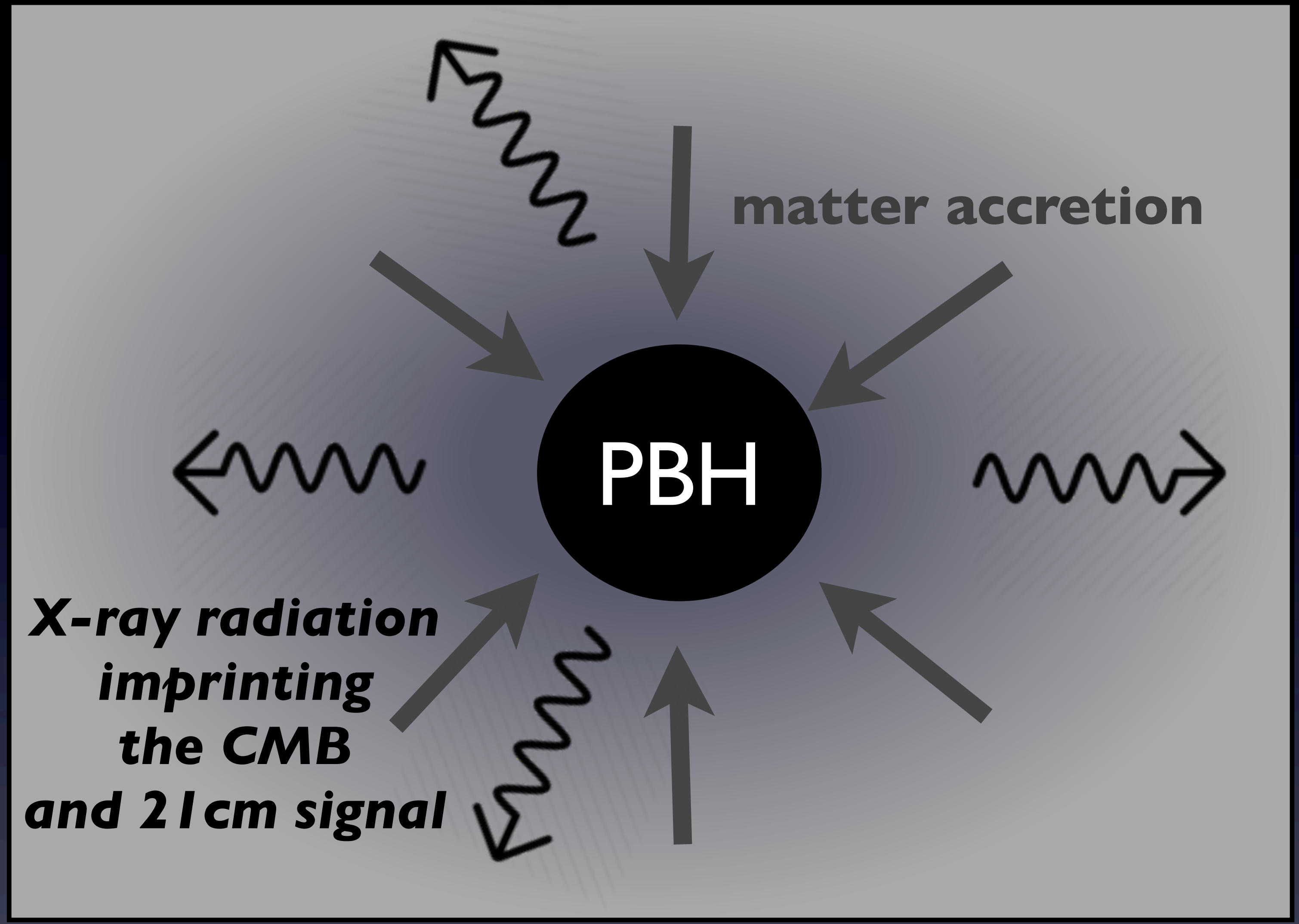


...and future prospects

- Detecting a BH below the Chandrashekar mass (LIGO)
- Numerous merging events seen in GW detectors (LIGO, VIRGO, ET...)
- GW Stochastic Background (PTAs, LISA, LIGO)
- Detecting faint dwarf galaxies (DES, Euclid)
- Microlensing surveys (Euclid)
- 21cm signal (SKA)
- CMB distortions (PIXIE)
- Star position and velocities (GAIA)

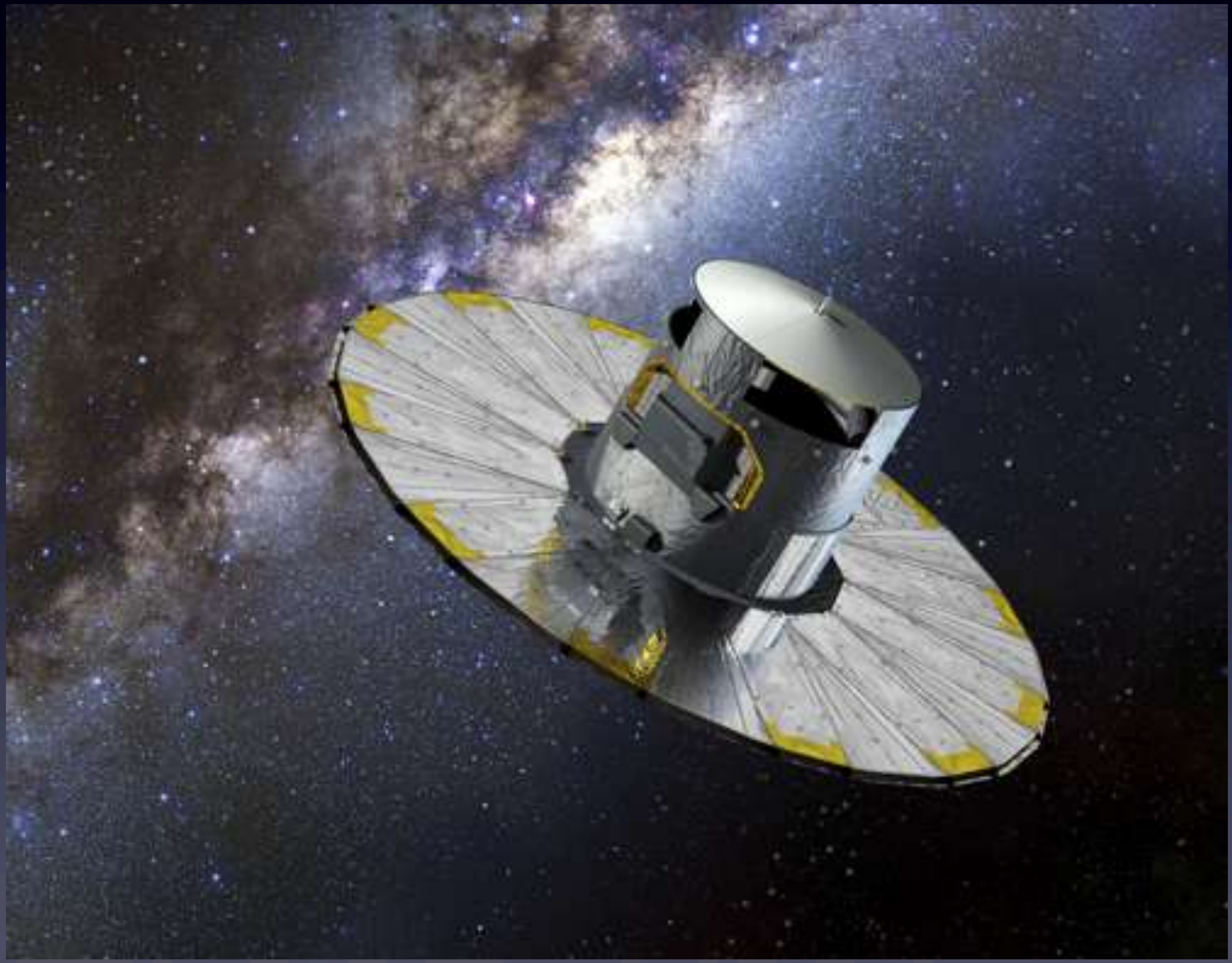
...and future prospects

- Detecting a BH below the Chandrashekar mass (LIGO)
- Numerous merging events seen in GW detectors (LIGO, VIRGO, ET...)
- GW Stochastic Background (PTAs, LISA, LIGO)
- Detecting faint dwarf galaxies (DES, Euclid)
- Microlensing surveys (Euclid)
- 21cm signal (SKA)
- CMB distortions (PIXIE)
- Star position and velocities (GAIA)



...and future prospects

- Detecting a BH below the Chandrashekar mass (LIGO)
- Numerous merging events seen in GW detectors (LIGO, VIRGO, ET...)
- GW Stochastic Background (PTAs, LISA, LIGO)
- Detecting faint dwarf galaxies (DES, Euclid)
- Microlensing surveys (Euclid)
- 21cm signal (SKA)
- CMB distortions (PIXIE)
- Star position and velocities (GAIA)



Other's approach:

LIGO rates and observations are intriguing,
so let's definitively rule out the possiblity
that Dark Matter is made of PBHs...

Our approach:

LIGO rates and observations are intriguing,
so let's find evidences that PBH are there
with comparable abundances to Dark Matter,...

We will know soon...

Thank you
for your attention

Initial clustering effect on the collapse of early binaries